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FINAL REPORT
APPLICATION OF MATERIALS-RELATED SYSTEMS ANALYSIS FOR RELIABILITY ENHANCEMENT IN LOAD-BEARING STRUCTURES
PHASE-II YEAR 1

by

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1. RESUME

Assurer la fiabilité de grands systèmes sous pression et d'ouvrages soumis à des charges fait intervenir de nombreuses disciplines allant du génie des matériaux et de la mécanique, à l'inspection non-destructive. Les incertitudes décelées par toutes ces disciplines se traduisent par une incertitude quant à la performance de ces ouvrages. Les incertitudes concernent principalement les défauts dans le matériau, leur caractérisation et leurs effets sur la capacité de l'ouvrage à supporter la charge.

On a élaboré et combiné des méthodes probabilistes pour caractériser les défauts et procéder aux opérations d'inspection et de réparation, dans le but de déterminer des distributions de la taille des défauts et leurs transformations en fonction du temps. On s'est servi d'une fonction de coupure (qui tient compte des effets d'inspection et de réparation) pour établir les distributions de la taille des défauts et pour analyser les avantages d'une inspection des ouvrages soumis à des mécanismes de dégradation comme la corrosion et la corrosion par fatigue, après leur mise en service. On a élaboré et quantifié un modèle généralisé que l'on a utilisé pour un oléoduc. Le modèle est basé sur l'analyse probabiliste des défauts: il admet le caractère probabiliste de plusieurs grandeurs comme la distribution de la taille des défauts, la probabilité de non-détection et la loi de croissance. On a déterminé le temps optimum pour l'inspection en service et on a évalué la sensibilité des caractéristiques d'inspection et des règles de réparation sur divers paramètres qui caractérisent le mécanisme de dégradation. Les résultats de l'estimation des avantages de l'inspection et des risques de défaillance sont présentés. Ces résultats découlent d'un ensemble de données recueillies lors d'une étude de la corrosion d'un oléoduc. On présente aussi des exemples d'études de sensibilité effectuées à l'aide du programme FRACTROL à partir du même ensemble de données.

On a élaboré un modèle qualitatif du phénomène de dégradation (fissuration) dans des rouleaux à succion. Ce modèle a été considérablement corrigé et amélioré à la fin de la présente étape du programme, à la lumière de résultats récents obtenus par les chercheurs de l'IGM. On a modélisé l'évolution de la population initiale des défauts pendant la durée de vie des rouleaux, dans des conditions de charge répétée. Ce modèle sera introduit dans le programme informatisé FRACTROL lors d'une phase subséquente du projet.

1. ABSTRACT

Assuring the reliability of large load-bearing and pressurized systems involves many engineering disciplines from materials and mechanics to nondestructive inspection. Uncertainty prevails throughout these disciplines resulting in uncertainty in performance of these structures as designed. Uncertainty focusses on the flaws in the material, their characterization and their actual effect on the load carrying capability.

Probabilistic procedures for characterisation of the flaws and inspection and repair operations, have been developed and combined to describe flaw size distributions and their transformations as a function of time. A censoring function for the flaw size distribution has been used to analyze the benefit of in-service inspection on engineering structures which undergo such degradation mechanisms as corrosion and corrosion-fatigue. A generalized model has been developed and quantified and an example provided for the case of an oil pipeline. It is based on probabilistic defect analysis. The model admits of the probabilistic character of several quantities such as flaw size distribution, non-detection probability and growth law. The optimal time for in-service inspection has been determined and the sensitivity of inspection characteristics and repair policies to various parameters which characterize the degradation mechanism has been assessed. Results of estimation of the inspection benefit and failure assessment for a set of data from a corrosion survey of an oil pipeline are presented as well as the example of sensitivity studies performed with the FRACTROL program for the same case are given.

A qualitative model of the degradation (cracking) phenomenon in suction press rolls was developed and outlined. This model was considerably revised and upgraded late in this program period using recent results obtained by IGM scientists. The evolution of the initial population of defects during suction roll life under repeated loading has been modelled and prepared to be introduced into the FRACTROL computer program in a subsequent phase of this project.

2. INTRODUCTION

This Final Report is submitted as a requirement under the Contract No. 11SD. 31155-0-5008-1 entitled "Applications of Materials-Related Systems Analysis for Reliability Enhancement in Load-Bearing Structure - Phase II - Year 1". The report covers all work done under the basic contract during the period February 11, 1982 through February 10, 1983.

In this report, methods are outlined for optimizing the inspection procedures for large structures with respect to level and frequency and for predicting service lives. These methods are discussed with respect to their application to oil and gas pipelines and suction rolls in papermaking machines. The analysis addresses the question of materials-related aspects of failure due to deterioration.

The research project was focused on two aspects of Materials-Related Systems Analysis:

a) Theoretical development of models describing the censoring of flaw size distributions due to inspection and repair.

and b) Practical application of materials-related system analysis in two representative industrial applications.

In addition to these two general areas of research investigation, a comprehensive system analysis approach has been used to model the concept of life-time and the parameters relating to life-time for structures where failures result from damage accumulation by corrosion, corrosion-fatigue, stress-corrosion cracking and other time-dependent failure mechanisms.

Late in the program period, modelling concerning the degradation mechanisms (cracking) in paper-making machine suction rolls was modified to accommodate the most recent observations of IGM scientists. This quantification of the degradation mechanism which takes place in suction press rolls introduces new modeling details to be implemented into the FRACTROL program giving a higher degree of confidence for producers and users.

3. TECHNICAL DESCRIPTION

3.1 The General Systems Approach

The purpose of systems engineering is to solve problems beyond the scope of any one individual or discipline. It is essential to look initially at the problem generally in terms of objectives and constraints without becoming involved in detail. The system analyst then proceeds to add detail through logic modeling. This provides the advantage of precisely defining the information required and adds efficiency to problem solving.

Operation research and systems analyses are the most important offsprings of the systems approaches. Operations research comprises a diverse set of "cookbook" approaches to narrow and specific problems. Systems analysis represents the same approach when the problem is generalized to larger systems and used for administrative purposes. The techniques available include statistics, simulation and Monte-Carlo methods, linear programming, guessing theory, decision theory, game theory, simulated games, cybernetics and information theory. In constructing systems analysis as a discipline, the systems theorist draws heavily on these disciplines.

For those components of a load-bearing system which operate under load, there are two distinct design criteria to be considered - strength-based design or analysis of the behavior of the structure according to its constitutive equations and failure-based design. Failure based design recognizes the basic fact of life that materials contain flaws or that flaws may be introduced in service. These flaws and their effect on materials performance must be characterized. Thus, an integral element in assuring the integrity of load-bearing structures subject to degradation of their materials of construction involves inspection. The inspection process is carried-out during fabrication, before the structure is put into service and periodically during its service life.

Interrelations among failure control disciplines can be represented in a general form using the central formula of systems analysis, the block diagram with arrows representing inputs and outputs. Three types of operations - conversion operations, logical operations, and correction operations - may be combined and multiplied to any level of complexity. Common types of such operations include the transformation block in which input x is converted to output y by specified conversion rules (Fig. 1a). In the decision block, input x is tested and converted to either y or z according to stated rules (Fig. 1b).

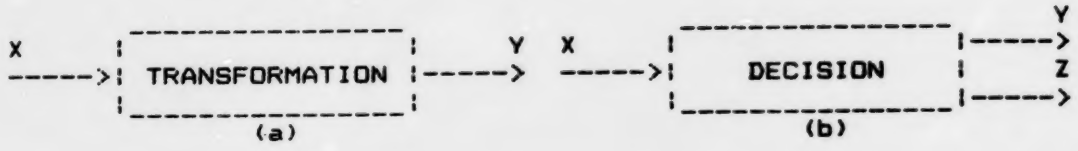


Fig. 1 Transformation and decision operations

In the feedback block, input x is modified as a function of output y (Fig. 2)

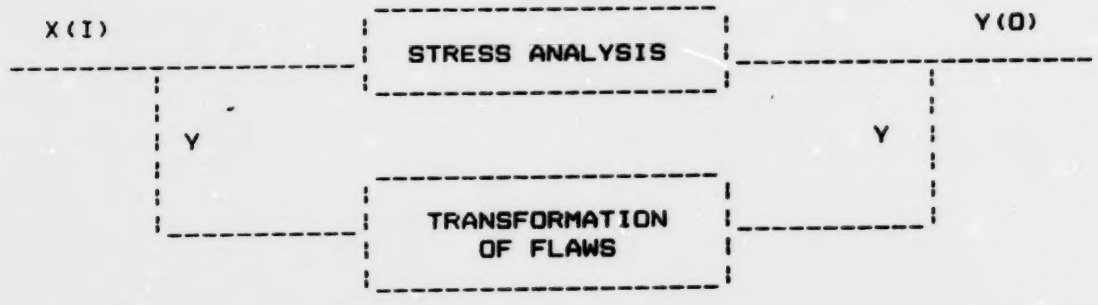


Fig. 2 Feedback operation

Each of the elements in the failure analysis and control system can be identified in terms of the operation it performs. They can be combined in an appropriate fashion to effect the required analysis.

The systems approach adopted here comprises four phases. Initially, in the informational input phase, the system is defined from an operational or functional viewpoint rather than in mechanistic terms. This can include selection of the key system output(s) required to characterize its behavior or performance or to effect judgements or decisions and comparison of the observed behavior with design objectives and overall cost implications. Management value judgements and attitude toward risk may be involved. In addition, the set of key inputs over which control can be exerted are defined thereby completely describing the system in terms of its inputs and outputs. In the next phase of system development, the deterministic phase, crucial variables are identified and the problem is structured and modeled. In the probabilistic phase, uncertainty about crucial variables is encoded and the profit lottery calculated. The informational output phase involves validation and implementation of the model.

The result of the informational input phase is a comprehensive description of the problem in terms of its inputs and outputs.

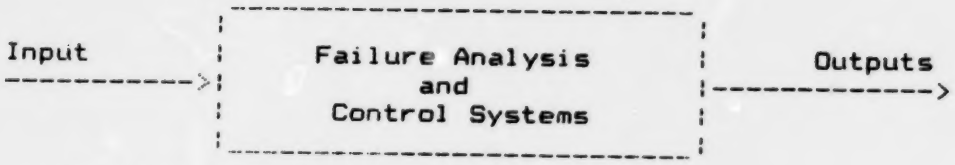


Fig. 3 Definition of the system in operational terms

The elements of the failure analysis and control system include the:

- loading condition characterization, the
- flaw characterization, and the
- material failure resistance characterization and cost functions.

A loading condition characterization involves determining the effect of load on the structure. Load-deflection, pressure-strain, and other similar calculations based upon the constitutive relationships are, in effect, transformation operations. Similarly the flaw growth laws which characterize the material failure resistance are also transformation operations. The term degradation is used to describe this type of transformation. In a failure control system, flaw characterizations by inspection are accompanied by a corrective action such as repair or scrapping. The term upgradation has been coined for the inspection/correction transformation. Three basic transformations are summarized in Table I.

TABLE I Transformation Operations

Stress analysis
Degradation - flaw growth
Upgradation - inspection/correction

TABLE II Decision Operations

K_{IC}	Plane strain fracture toughness
K_c	Fracture toughness
K_{th}	Threshold stress intensity factor for fatigue
K_{ISCC}	Threshold stress intensity factor for stress corrosion

In addition to transformations, materials science and fracture mechanics provide a basis for certain logical operations. These include the use of critical values of the stress intensity factor including the fracture toughness K_{Ic}, the threshold stress intensity for fatigue crack growth K_{th}, and the stress corrosion cracking threshold K_{Iscc}. In such a decision box a parameter is monitored (the stress intensity) and a decision made as to whether a particular failure mechanism is operative. These decision operators are listed in Table II.

Examining the transformation operations in more detail, they clearly separate into two categories. The response of a well-characterized structure to a load is characterized by its constitutive equations. These are based upon equilibrium theories of classical thermodynamics and may be considered as reversible or quasi-static processes. On the other hand, the degradation mechanisms are clearly irreversible. Thus the qualitative model should recognize this distinction and separate them into two modules.

Many deterioration mechanisms, such as fatigue and stress corrosion, depend upon the loading conditions and require information from the constitutive equation block. Similarly, as the severity of corrosion or fatigue attack increases, the flawed areas attain a size where they may modify the geometry upon which the stress analysis is based. Thus, the irreversible phenomena act as a feedback block which controls the constitutive equations (Fig. 4).

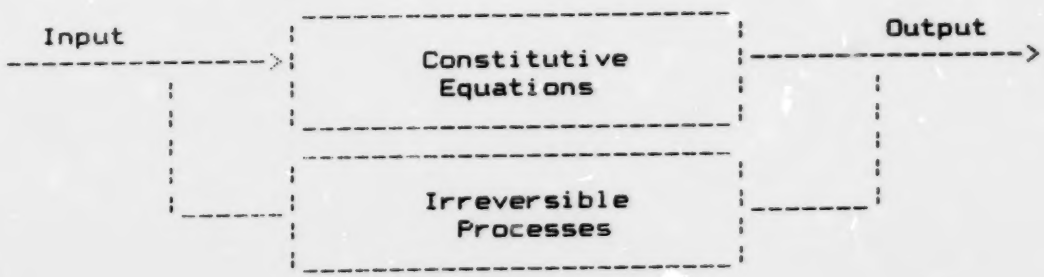


Fig. 4 Feedback operation in a failure analysis and control system

Here top-down modeling has clearly separated the phenomena according to fundamental concepts and established the information flow on a basis analogous to control theory.

Expanding the irreversible process block to show the degradation and upgradation processes gives the block diagram in Fig. 5.

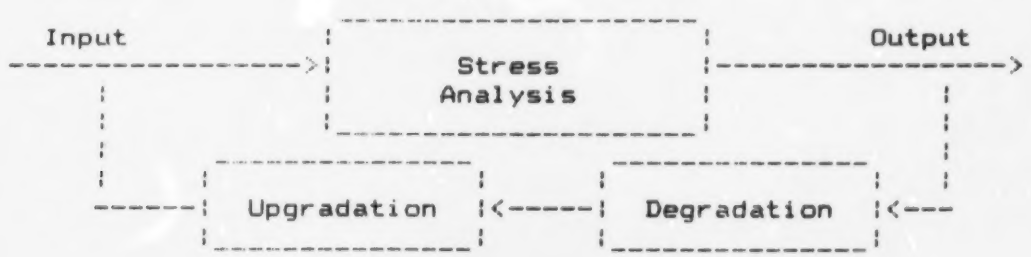


Fig. 5 Basic failure control flow diagram

This diagram illustrate the basic flow of information in the failure analysis and control system. It is the fundamental system upon which more elaborate systems can be built to incorporate economic and administrative factors and multiplicities of failure modes.

3.2 Materials-Related Aspects of Failure

Failure rates of complex systems follow a familiar pattern. The failure rate as a function of time exhibits three distinct zones as shown in Figure 6. High failure rates which occur early in the service life may develop as a result of design or manufacturing deficiencies or of errors in usage, misapplication or other identificable causes. This initial period of high failure rate is called the infant mortality period . This is followed by a constant failure rate period. Failures in this period result from inherent design limitations, inadequate maintenance or service-induced accidents. The final period, characterized by an increase in failure rate, is the wear-out period. Various mechanisms come into play, including metallurgical embrittlement and accelerated corrosion and fatigue.

Materials-related modes of failure are defined, for this report, as those produced by time-dependent deterioration mechanisms such as corrosion and fatigue. The ultimate manifestation of these mechanisms is a crack-like defect which propagates to a size at which the integrity of the structure, or its load carrying or containment capability, is compromised. In addition to defect generation and growth by the deterioration mechanisms, the initial flaw content and configuration may play an important role in the overall progress of deterioration. This definition excludes chance events such as damage by others to the structure which can lead to failure. Although the inspection optimization procedures to be outlined later may be applied to the case of such chance

failures, the predictive capability obtained from established flaw generation laws for time-dependent phenomena would not be available. The chance failures can be treated using a "materials-related" analysis which incorporates growth laws for the metallurgical mechanisms that develop in the damaged region. It is, however, important to emphasize also that all the materials-related failures are subject to uncertainty and are treated on a probabilistic basis.

3.3 Structuring the Model

Models of varying complexity now appear in the literature with increasing frequency. They are spread over a highly diverse body of literature varying from general materials and reliability journals to specialized trade literature. There is, however, a certain conceptual framework which has not been formalized and which provides a certain commonality of approach.

Now, there is a growing interest in the application of probabilistic defect analysis (PDA) to the prediction of failure probabilities for a number of large-scale engineering structures such as aircraft, ships, pressure vessels, offshore platforms and rotating machinery. Probabilistic fracture mechanics provides a failure criterion in terms of size, shape and location of a crack-like defect, the stress in the structure and the characteristics of the material. These criteria are complemented by models of the nucleation and growth of flaws by various degradation mechanisms as well as models of the effect of inspections and accompanying correction operations. Thus, probabilistic defect analysis can lead to complex models involving several disciplines.

Since failure in a structure is often a complex interaction of metallurgy, mechanics and chemistry and the methods of PDA itself are a mixture of probability, reliability and operations research, the multidisciplinarity can make synthesis of a unique and general framework difficult. Thus, a simple systems approach has been adapted to this problem to identify the information content in a probabilistic manner and to define the way in which information flows in the system as the reliability is influenced by materials degradation and inspection/correction operations.

This threefold concepts shown in Figure 7. Although there is not a general consensus on exactly which of these categories is to contain specific parameters, STRESS is a generic term for all external solicitations including environmental and operating conditions. The MATERIALS category contains descriptions of the materials mechanisms responsible for flaw initiation and propagation. In the DEFECT category, such factors as the inspection method used to detect flaws, the evaluation of flaw significance, and the repair or correction procedures used, are considered.

Once the information content is defined, information flow is shown in Figure 8 as a simple feedback system as described in Section 3.1. Invariably, the various models in the literature reduce to this simple cybernetic model where stress and strength of materials analyses remain the backbone of the evaluation of the load-bearing capacity of a structure. Materials and defect-related analyses are superimposed through a feedback link. For example, materials degradation phenomena such as stress corrosion and fatigue are controlled by stress parameters. They operate on this information to produce flaws which are characterized by a flaw size (or flaw size distribution). This flaw size is operated on periodically by an inspection/correction (or upgradation) box and the resultant flaw size (or flaw size distribution) is returned to the stress analysis to determine its effect on the load-carrying capacity of the structure. This cybernetic model of the PDA problem provides a general framework for all calculations of this kind.

Having developed this general description of the PDA problem, one should abandon generality, while retaining the system structure, because the systems would become exceedingly complex if the top-down approach is continued. It is necessary to begin bottom-up construction of specific models which are subsystems of the feedback system in Figure 8.

3.31 Initial Flaw Size Distribution

The statistical description of the flaw population is generated in the degradation module. The probability density function for this flaw size population is needed, firstly, as an initial condition which is then transformed as a function of the time in service. This extremely important input parameter is modeled in terms of the original flaws existing after fabrication and those introduced by various degradation mechanisms during the service life.

Several different distributions corresponding to different types of flaws may exist in the same structure. The problem of selecting and transforming these distributions is not simple and several authors have considered this problem for specific cases with various assumptions. A number of different types of distributions have been used for the initial flaw size distribution. These include several functions as the exponential, normal, log-normal, gamma, Weibull, beta, Pearson, Gumbel and almost any function known to date. The functions used by a number of researchers are shown in Table III with the objectives of their analysis.

Related to the statistical model of the initial flaw size is the distribution of the number of flaws that are likely to exist in a given structure. In general, the Poisson distribution has been proposed for the number of defects. Estimates of the number of defects in reactor pressure vessels and piping have been made

giving results which are generally very divergent. The basic assumption in such analyses is that the total number of defects of all sizes will be proportional to the volume of the material in which they occur, while the probability distribution function will be common to a range of structures made from similar materials. It is widely recognized that the failure probability, or reliability, is directly proportional to this number. Thus, it is important to obtain acceptable estimates of this quantity and a better understanding of the factors which control it. A summary of the number of defects found in certain structures is given in Table IV.

3.32 Uncertainties of Inspection

Flaw characterization for probabilistic defect analysis purposes involves preservice inspection before the structure begins its useful service life and periodic in-service inspections throughout the service life. The preservice inspection conducted just prior to entering into operation evaluates the quality of fabrication and installation quality control. It is designed to give assurance of integrity up to the first in-service inspection. However, even the most stringent preservice inspection is subject to some uncertainty leading to a small but non-zero probability of the structure entering service containing some defects. When these defects can initiate, a characterization of the flaw size distribution and of the detection capability of the inspection method used to detect and measure the flaws is a basic input to the probabilistic defect analysis.

In-service inspections are usually preplanned to be carried out at regular intervals. They may also be initiated by the occurrence of failure or the chance detection of a prematurely large defect. More recently, the codes for nuclear reactor pressure vessels have been amended to allow an alternative to inspections at regular intervals. Using probabilistic defect analysis, an optimal sequence of inspection can be developed to achieve higher levels of reliability.

The ability of both preservice and in-service inspections to detect and describe existing defects depends upon many factors including the size of defects and is expressed as a probability of detection or non-detection as a function of size. Detection capabilities vary widely with inspection conditions. Working conditions, accessibility, surface conditions are among the important factors. In general, preservice inspections carried out during and after manufacturing are much more effective than the best of in-service inspection. The latter can only be considered as useful in detecting the defects which have developed significantly in service rather than a backup check for manufacturing defects missed in the preservice inspection.

Simple theoretical models in the past have assumed that the inspection methods are infallible in revealing all unacceptable deterioration and that repair totally rectifies any deterioration. Probabilistic defect analysis recognizes that these methods are somewhat less than perfect and quantifies their lack of perfection which could lead to failure.

The probability of detecting a defect, if it exists, depends on the size of the defect and the resolution capability of the particular non-destructive inspection technique employed. This quantification of the inspection capability implies that there is no absolute guarantee of finding or missing a defect in a single inspection observation but only a probability of success with a given confidence value. The following functional form for the detection probability is available in the FRACTROL program

$$PD(a) = \begin{cases} 0 & ; \ a < a_{th} \\ [(a - a_{th})/(a_{max} - a_{th})]^m & ; \ a_{th} < a < a_{max} \\ 1 & ; \ a_{max} < a \end{cases} \quad (1)$$

where PD (a) is the probability of detecting a defect with size equal to a. a_{th} is the defect size below which a defect cannot be detected, and a_{max} is the defect size beyond which a defect can be detected with certainty. In this equation, m is a parameter to be determined empirically.

Another equation for the crack detection distribution function is

$$PD(a) = \begin{cases} 0 & ; \ a < a_{th} \\ C_1 [1 - Exp(-\beta_1 (a - a_{th}))] & ; \ a > a_{th} \end{cases} \quad (2)$$

where a_{th} has the same meaning as before, C has a value slightly smaller than unity to allow for the small, but finite probability of missing a large flaw during inspection.

Information on the reliability of field inspections has not been quantified in terms of the statistical distribution function. However, reliability of a field in-service inspection is much lower than that under laboratory-controlled conditions. Although the distribution functions of defect detection in service have not been proposed in the literature these equations or others can be used with larger values for a_{th} and a_{max} to fit the service inspection data as it becomes available. One can expect that the higher the resolution capability of an inspection method, the higher the in-service structural reliability. However, a better NDI method is usually accompanied by a higher inspection cost, and it should be balanced by the overall expected cost, risk or utility.

In addition to the uncertainty in the detectability of a defect, there is a further uncertainty in the size attributed to the defects. The defects may be much larger or smaller than they appear from the inspection indication.

Considering for example the general performance of the best ultrasonic techniques in sizing a fatigue crack, statistical analysis show that to be highly certain that a crack is no greater than, say 20 mm in size, it must be measured to be no more than 5 mm. The main factors which cause the variation are procedure and equipment variables, defect orientation, transparency, coupling factors, operator variables, defect roughness, interference effects and attenuation. It is the resolution of the inspection system which determines the smallest defect whose shape can be recognized, and also the precision of size measurement for larger defects.

Although all techniques give the same information on defect size and position, almost all the conventional techniques tend to undersize the through-thickness dimension. Conventional ultrasonic testing is generally reliable for positioning and defect length estimation. Ultrasonic holography provides accurate position and defect length information but grossly overestimates through-thickness size.

High frequency eddy-currents induced in a component have a skin effect and that influences the impedance and phase relationships. The net effect is that although eddy-current devices are useful for crack detection in general and also for sizing shallow cracks in light alloy, they are less suited to sizing deeper defects in steel structures. A further limitation is that errors are generally an underestimation.

3.33 Degradation Mechanisms

Failures occur when the strength or resistance of a component and the load or stress imposed on it become incompatible. Therefore, the deterioration of material strength by time-dependent degradation mechanisms such as general corrosion, fatigue, corrosion-fatigue, and stress corrosion will determine the time to potential failure. These degradation mechanisms are continuous functions along the materials, stress and environment vectors. Furthermore, in many applications, the deterioration processes are multiply-connected. In such cases, failure is not the simple accumulation of damage by corrosion, fatigue, corrosion-fatigue or stress-corrosion. Rather, it is multi-modal wherein one mechanism operates and triggers the onset of another. Thus, in the failure of certain mechanical systems, the first mechanism may be corrosion which produces pits. These subsequently grow to a critical depth which then induces a second degradation mechanism

such as corrosion fatigue or stress-corrosion cracking depending on environmental and stress conditions. The total time to failure may not be dominated b the final mechanism but rather by one of the preliminary, but critical mechanism(s).

Although other degradation mechanisms exist such as creep and metallurgical degradation due to exposure to radiation or elevated temperatures, the four mechanisms listed above are responsible for an overwhelming majority of losses in contemporary structures. In good structural design the possibility of their acting together must be considered.

At the beginning of service life, it is possible to define a characteristic flaw which can be described by a characteristic length, x. This characteristic flaw is a part of a larger flaw size population and is selected in order to monitor the level of degradation of the structure. It is the critical value of this parameter which defines the terminal condition for a structural unit. The characteristic flaw size has an initial known probability distribution usually determined by quality control at source or preservice inspection.

The characteristic flaw size increases according to a known deterministic or probabilistic growth law which is usually a function of time and flaw size. At a certain time, t, during the service life, an inspection operation takes place followed by the repair or replacement of units which contain a flaw size greater than or equal to a tolerable size. Since there exists a finite probability of non-detection inherent in any NDT equipment, some flaws will remain in the structure, represented by the shaded area in Figure 9. This process is shown in the same figure and expressed mathematically as follows:

$$f_c(x) = PND(x) * f_t(x) \qquad (3)$$

where $f_t(x)$ is the size distribution before inspection, PND(x) is the probability of non-detection, and the product of these two expressions, $f_c(x)$, is the flaw size distribution after inspection.

From Figure 10, it can be seen that two flaw sizes can be specified, namely: the tolerable size, a_{tol}, and the failure size, a_f. The latter may also be thought of as a critical size, i.e., the size of a flaw in which the failure of a system is imminent. Hence, the units containing a flaw greater than or equal to a are put out of service and replaced with a brand new unit. The fraction of the population that needs to be replaced is represented by area A in Figure 10.

The tolerable size, on the other hand, may be a variable parameter. However, if one uses a deterministic growth law, then a is unique: it may be calculated such that it is the flaw size at

the inspection time which will grow to a critical value, a_f, by the end of the service life. However, if one uses a probabilistic growth law, there is a whole range of flaw sizes each one having a finite probability of reaching a_f. In this case, a_{tel} is not unique and hence, must be specified.

The relevance of a_{tel} is that, in the case of a deterministic growth law, this determines the fraction of flaws that need to be repaired to reduce the probability of failure by the end of service life. For the case of probabilistic growth, a_{tel} would have to be specified and may be thought of as the repair size. In both cases, only the flaws filtered or censored are assumed to be repaired. This is represented by area B in Figure 10.

This is only one policy. In fact, one may specify all flaws censored to be repaired. This, of course, is the extreme case. In Figure 10, these flaws are represented by area (B + C).

For the flaws that have been repaired and replaced, one may assume certain distributions, $f_\pi(x)$ and $f_o(x)$, respectively to describe the state of these flaws. For example, $f_o(x)$ may be assumed the same as the original system's flaw size distribution. These distributions will serve as weighting factors in redistributing the flaws. This procedure can be illustrated mathematically as follows:

$$f_{new}(x) = A f_o(x) + B f_\pi(x) + f_t(x)_{x < a_{tel}} + f_c(x)_{a_{tel} < x < a_f} \quad (4)$$

where $f_{new}(x)$ is the reconstructed distribution; $f_o(x)$ is the original system's flaw size distribution, assumed also for the replaced flaws; $f_t(x)$ is the flaw size distribution prior to inspection which is generated using a flaw growth law applied to the initial flaw size distribution; and $f_c(x)$ is the censored distribution. These parameters along with A, B, a_{tel}, and a_f are represented graphically in Figure 11.

Stochastic Interpretation

Often in engineering situations, one considers observations of a phenomenon over a period of time which are influenced by chance or random effects, not just at a single instant but throughout the entire interval of time or the sequence of times under observation. This situation is termed a stochastic process. Examples are very diverse. Processes of interest to a design engineer would be those that relate to material degradation leading to mechanical failure such as fatigue, pitting corrosion, stress corrosion, and corrosion fatigue. These degradation modes, in general undergo two simultaneous processes prior to failure, namely: flaw initiation and growth. Depending on the nature of

the environment and loading conditions, one process predominates over the other. In any case, both can usually be described stochastically.

In a rough sense, a stochastic process is a phenomenon that varies unpredictably with time. The unpredictability here implies that if an entire time-sequence of the process is observed on several different occasions under presumably identical conditions, the resulting observation sequences, in general, would be different. Probability enters, but not in the sense that each result of a random experiment determines only a single number. Instead, a random experiment determines the behavior of a system for an entire sequence or interval of time. That is, the result of the random experiment is a sequence or series of values, a function, not just a single number.

Since a stochastic process involves the behavior of a system in time, in defining such a process it is necessary to specify the time set T involved. This might be some non-denumerable time interval such as:

$$T_1 = \{t \mid t>0\}$$
$$T_2 = \{t \mid -\infty < t < \infty\} \qquad (5)$$

or in another case, T might be a denumerable sequence of times such as:

$$T_3 = \{0, 1, 2, 3, \ldots.\}$$
$$T_4 = \{\ldots., -2, -1, 0, 1, 2, \ldots.\} \qquad (6)$$

Processes with index sets such as T_1 and T_2 are called continuous parameter processes while those with index sets such as T_3 and T_4 are called discrete parameter processes.

Suppose that at each point t of the time set T, a measurement of random variable X_t can be observed. Thus, a given random experiment is assumed and for each sample point or experimental outcome there corresponds not a single number (as in the case of a random variable) but an entire function X_t. If the sample point or experimental outcome is denoted by ζ then the function can be properly denoted by:

$$X_t(\zeta) \quad \text{for } t<T \qquad (7)$$

Such a random function of t is termed a stochastic process or random process. A single sequence of observations (or function) X_t that corresponds to a single sample point ζ is termed a realization of the stochastic process. The range of X_t (the collection of numerical values that the random variable X_t can

take on) is termed the state space of the process, and the values of X_t are termed states. If X_t represents some measurement (temperature, voltage, etc.), then the state space might be an interval of real numbers. If X_t represents a count, or a whole number of objects, the state space might consist of a sequence (finite or infinite) of integers. The former case speaks of a continuous state process whereas the latter case speaks of a discrete state process. Hence, it is clear that there is a convenient way to distinguish four classes of stochastic processes, namely:

1) Discrete processes with discrete parameters, also sometimes called discrete random series or discrete random sequences. Here, the random variable takes on only discrete values at any time t and the parameter t assumes only discrete values.

2) Discrete processes with continuous parameter, also sometimes called discrete random processes. Here, the random variable is discrete but the parameter t takes on a continum of values.

3) Continuous processes with continuous parameters, sometimes just called continuous random processes.

Note that for a fixed value of t, X_t is a random variable that describes the state of the process at time t. Given any finite collection t_1 , t_2 , ..., t_m of times, then X_{t1} , X_{t2} , ..., X_{tm} is a set of n jointly distributed random variables. The probability structure of the process X_t is completely determined provided that the joint distribution or density function of each such set of random variables is determined. Basically, the analysis of a stochastic process involves determining the joint distributions and using them to predict the behavior of the process in the future, given certain behavior in the past. Thus, by imposing suitable restrictions on their n-dimensional distribution or density function, one can define the following as other classes of stochastic processes:

i) Stationary processes: whose joint distribution functions are invariant to time translation.

ii) Gaussion (or normal) processes: whose joint distibution function are multivariate normal.

iii) Markov processes: given the value of X_t , the values of X_s , s>t, do not depend on the values of X_u , u>t; in other words, the future behavior of the process, given its present state, is not changed by the additional knowledge about its past.

For a fixed value of t, X_t is a random variable that describes the state of the process at time t. Given any finite collection t_1 , t_2 , ..., t_n of times, then X_{t1} , X_{t2} , ...X_{tn} is a set of n jointly distributed random variables. It can be said that the probability structure of X_t is completely determined provided that the joint distribution or density function of each such set of random variable is determined.

In complex problems, the determination of the density function and the various conditional probability density functions may be very difficult. In surprisingly many practical problems, however, certain general simplifications are possible that greatly reduce the mathematical difficulty. The most important simplification is that in which, if the system is known to have reached state i at the (n-1) st stage, it is immaterial what chain of states it passed through on the way to this stage as far as predicting (giving probabilities for) the state it will enter at the next stage is concerned. This situation is referred to as a Markov process. For example, give a random sequence or discrete random process $\{X_1 , X_2 ....\}$, it is a Markov process if it has the property that, conditional on knowing the value of X_{n-1} ("the present state"), the probability that X_n will take on some given value ("a future state") will be unaffected by the knowledge of the values of X_1 , X_2 , ..., X_{n-2} ("the past states"). That is:

$$P\{X_n = i_n \mid X_1 = i_1 , \ldots, X_{n-1} = i_{n-1}\} = P\{X_n = i_n \mid X_{n-1} = i_{n-1}\} \quad (8)$$

Many real-world processes can beconsidered as a Markov process, in particular, the corrosion process.

For example, corrosion processes in pipelines are many-fold. At present, field inspection techniques exist for detecting and characterizing the general pitting corrosion. The latter is defined for the purposes of this example as localized corrosion which occurs in discrete areas where extent can be characterized by a single depth measurement. Corrosion processes are of a stochastic nature [32 - 34] and, thus, the phenomenological description of both pit initiation and propagation processes can be formulated using the theory of stochastic processes.

The inherent randomness in pitting corrosion arises from the high degree of complexity of the metal/environment combination in which the process takes place. Variations in the metallurgy of, for example, a pipeline material at the microstructural level as well as in the local exposure conditions can produce large variations in both the actual local corrosion driving forces and resistance to corrosion and, therefore in local corrosion rate although nominal materials and environmental parameters appear uniform.

Using line pipe in oil and gas pipelines as an example, if the pit depth, x, or degree of pipe wall penetration is observed as a function of time, the depth of an individual pit is a monotonically increasing function of time. The average pit depth of a population of pits behaves in the same way and Figure 12 shows such an average with the distributions of pit depths at two different times. Some of the expressions used for $x(t)$ that have been proposed to describe pit growth are listed in Table V.

If at time t_1, t_2, ... of the time set T, a measurement of the random variable $X_1(t_1)$, $X_2(t_2)$, ... can be observed, then a succession of these random variables following each other in time defines a stochastic process. Note that for a fixed value of t, X(t) is a random variable that describes the state of the process at that point in time. Given any finite collection, t_1, t_2, ..., t_n, of times, then $X_1(t_1)$, $X_2(t_2)$, ..., $X_n(t_n)$ is a set of n-jointly distributed random variables. The probability structure of the stochastic process, X(t), is completely determined provided that the joint distribution or density function of this set of random variables is determined. Basically, the analysis of a stochastic process involves determining the joint density $f(x_1, \ldots, x_n)$ and using it to predict the behavior of the process in the future, given certain behavior in the past, i.e.,

$$f(x_n \mid x_{n-1}, \ldots, x_1) = \frac{f(x_1, \ldots, x_n)}{f(x_1, \ldots, x_{n-1})} \qquad (9)$$

where $f(x_n \mid x_{n-1}, \ldots, x_1)$ is the conditional density of x_n given the past history of the process.

For a "Markov" stochastic process. This equation becomes:

$$f(x_n \mid x_{n-1}, \ldots, x_1) = f(x_n \mid x_{n-1}) \qquad (10)$$

$f(x_n \mid x_{n-1})$ is called the transition density of the Markov process from which the transition probability can be defined, i.e.,

$$\begin{aligned} &P(X_n = x_n \mid X_{n-1} = x_{n-1}) && \text{discrete case} \\ &P(X_n \in E_n \mid X_{n-1} \in E_{n-1}) && \text{general case} \end{aligned} \tag{11}$$

where E is some statistical event where the probabilities are defined. Classical examples of the transition probabilities for a Markov process are given in Table VI. In general, these transition probabilities can be obtained experimentally or analytically. For the latter case, for example, Lomacky et al [7] derived the transition probability given a distributed fatigue crack growth rate (Paris law). In another application, corrosion (in general), Rao [34] derived the transition probability of a corrosion process under randomly varying exposure conditions. In both examples, the degradation processes were idealized as a Markov process.

A very important relation arising from this analysis, that which is useful in estimating reliability, is the following:

$$P_j(t) = \sum P_{ij}(t)\, P_i(0); \quad i > j \tag{12}$$

where

$$P_j(t) = P[X(t) = j] \tag{13}$$

is the absolute probability of being in the jth state after some time t,

$$P_i(0) = P[X(0) = i] \tag{14}$$

is the probability of being in the i^{th} state at time t = 0, and

$$P_{ij}(t) = P[X(t) = j \mid X(0) = i] \tag{15}$$

is another way of writing the transition probability, giving the probability of being in the state X = j at time t when at time zero X = i. Thus, for a Markov process, it is sufficient to specify relations (14) and (15) to describe the evolution of the process, i.e., relation (13). Equation (12) is thus very important

as far as reliability estimates are concerned because it is from here that one can obtain the interference with a critical crack size or a failure size distribution, the measure of risk or reliability.

3.34 Failure Modes and Criteria

Failure mode is defined as a way in which a component, or a structural system might fail. In order to estimate the probability of failure for a given mide, a thorough engineering analysis of potential or actual mechanical and structural failure modes should be performed based on a knowledge of the loads imposed by the environment in which the component operates and the resistance to these loads.

Some of the more important failure modes are:

- General yielding or excessive plastic deformation
- Buckling or general instability, either elastic or plastic
- Subcritical crack growth leading to loss of section or unstable crack growth

    a) fatigue
    b) stress-corrosion
    c) corrosion-fatigue

- Unstable crack extension, either ductile or brittle, leading to either partial or complete failure of a member.
- Corrosion (metallurgical) -- chemical failure.
- Creep

During the course of this project, the analytical models were programmed for execution on an LSI11/23 computer and designated as the FRACTROL programs. The FRACTROL program has, for the majority of these modes, functional causal models which can be used to perform a quantitative analysis of the probability of failure under the appropriate operating conditions.

The FRACTROL program develops logical models which estimate and quantify the effect of the largest defects that escape quality assurance detection (before and in-service). This analytical approach employs stress-strength interference theory to formulate the model. Therefore, to estimate the probability of failure for a given mode using interference theory, it is necessary to model the failure mode in terms of stress and strength. Depending upon failure model and the complexity of the component or system, failure starts at some "weak spot" and then propagates until there is so much deformation or so large a defect that subsequent events are catastrophic. In general there are certain limiting states which,m if exceeded, then failure occurs. Failure may occur in

different modes, for a component or system, and at present it is a common practice to estimate the mode most critical for a particular situation and plan to prevent it from occurring. In some instances an important mode may be overlooked, or, in others, more than one mode must be considered in detail.

From the most general viewpoint different criteria have been proposed to assess the total failure in terms of stress intensity factor or defect size such as:

$$P(F) = P(K \geqslant K_{IC}) \tag{16}$$

or

$$P(F) = P(a \geqslant a_c) \tag{17}$$

When non-critical failure is a local degradation of the pressure boundary, the extent of which exceeds acceptance criteria and which may or may not result in leakage of pressurized fluid, the failure extension can be expressed by:

$$P(F) = P(a \geqslant t) \tag{18}$$

where K and K_{IC} are applied stress intensity factor and fracture toughness, a and a_c are observed size of defect and critical size determined by a probabilistic defect analysis and t is the wall-thickness. In all the expressions it has been noted by $P(.)$ the probability of certain event such as failure for instance.

4. SYSTEMS APPLICATIONS

4.1 Pipeline System

Reliability may be defined as the probability that a component performs adequately for a specified period in a given environment. Suppose that pipeline system can be divided into regions as shown in Figure 13, where within each region the nominal metal/environment parameters are uniform. This important feature of this procedure enables the pipeline maintenance engineer to divide his system into regions in which, in his judgement or experience, the corrosion conditions is relatively uniform. In the case of failure by pitting corrosion, manifested as a leak or full wall penetration, the probability of failure for any one region is expressed in terms of leaks per unit length per unit time. Given P_{f_1} , P_{f_2} , ..., P_{f_n} , the probabilities of failure for regions 1, 2, ..., N, the probability of failure for the entire system P_{f_T} , is calculated as:

$$P_{f_T} = \frac{P_{f_1} * L_1 + P_{f_2} * L_2 + \ldots + P_{f_n} * L_n}{L_1 + L_2 + \ldots + L_n} \qquad (19)$$

where L_1 , L_2 , ..., L_n are the lengths of each region.

Consider now the calculation of the probability of failure, P_{f_T} , for one region given that failure occurs whenever a pit fully penetrates the pipe wall. A pit depth may be given in absolute units or, often, as a percentage of the pipe wall thickness.

Let

$$m f_X(x)\, dx \qquad (20)$$

be the average number of significant defects per unit length of a region at the time of inspection which have a depth in the range x to x + dx; m is the total number of significant anomalies divided by the total length of the region; while $f_X(x)$ is the probability density function describing the uncertainty in the size of the existing significant defects. The domain of $f_X(x)$ is defined between the detection threshold, x_{th} , and the full wall thickness, x_W .

If the properties of the metal/environment combination are determinate, then there will be a definite relation between the

depth of an anomaly, x_i, at the time of inspection, and x_t, its depth at a later time. This taken to be:

$$x_f = f(x_i, t) \tag{21}$$

Examples of this functional relationship are given in Table V. In reality, however, x_i and x_t do not have a one-to-one correspondence. More realistically, given x_i, x_f is a randomly distributed variable; a stochastic approach is required and since the growth process is Markovian, expressions such as in Table VI are necessary to relate x_i and x_f.

In this type of analysis, reliability calculations and predictions are usually based upon the existing flaw size distribution obtained at the last inspection. While it is indeed true that new flaws will be generated in the future and will make a finite contribution to the probability of failure as will those flaws whose size is less than the detection threshold, their effects are negligible compared to those of the existing flaws and will be neglected. Hence, m, the average number, will be held constant throughout the analysis. Only when characterized by a subsequent inspection will they be reconsidered.

Thus, knowing $f_X(x)$ and the relationship between x_i and x_f, deterministic or probabilistic, the future form of $f_X(x)$ can be calculated; denote it by $[f_X(x)]_t$. The probability of failure for the region can then be calculated from:

$$P_f = m \int_{x_w}^{\infty} [f_X(x)]_t \, dx \tag{22}$$

To account for uncertainties in inspection and repair, define the probability expression, $g(x)$, which gives the probability that a particular value of the anomaly depth, x, will escape detection and thus repair. Consider, for the moment, that only one inspection (at time t) will be carried out during the remaining service life. Let P_f be the probability of failure at that inspection time and P_f be the probability of failure at the end of service life. Then

$$P_f = m \int_{x_w}^{\infty} [f_X(x)]_t \, g(x) \, dx \tag{23}$$

Define a new function $h(x)$, i.e.

$$h(x) = \begin{cases} [f_X(x)]_t \; g(x); & x \geq x_n \\ [f_X(x)]_t & ; \; x < x_n \end{cases} \tag{24}$$

where x is some specified value of anomaly depth such that those anomalies whose depth exceeds this value are assumed to be repaired "good as new", hence, eliminated from the population. $h(x)$ will suffer another transformation during the remaining life, t. Denote this transformation by $[h(x)]_t$. The second probability of failure, P_{f_2}, can now be calculated as follows:

$$P_{f_2} = m \int_{x_w}^{\infty} [h(x)]_t \, dx \qquad (25)$$

The over-all probability of failure, P_{f_T}, is calculated from the knowledge of P_{f_1} and P_{f_2} as follows:

$$P_{f_T} = 1 - (1-P_{f_1}) (1-P_{f_2}) \qquad (26)$$

For more than one inspection, the same procedure is followed. In general

$$P_{f_T} = 1 - \prod_{i}^{n} (1-P_{f_i}) \qquad (27)$$

where i is the number of transformations.

To implement the methodology, consider the inspection data from five hundred and ninety-eight (598) miles of 34-inch diameter crude oil pipeline, built between 1962 and 1969, was used. The line was non-destructively inspected using the magnetic flux leakage technique in June of 1979. The type of inspection involved a "corrosion survey". Inspection consisted of passing a self-contained pipeline pig, instrumented for flux leakage monitoring, though the pipeline and recording magnetic anomalies in the body wall of the pipe. The inspection procedure considered only the largest flaw in each joint and classified it into three grades as follows:

Grade No. 1 - anomaly indications of more than 15% but less than 30% body wall penetration.

Grade No. 2 - anomaly indications of more than 30% but less than 50% body wall penetration.

Grade No. 3 - anomaly indications of 50% or more body wall penetration.

Hence, one flaw in Grade No. 3 is in fact one pipe joint whose maximum flaw size exceeds 50% or more body wall penetration. Furthermore, anomaly indications which are believed not to be associated with significant deterioration of the pipe wall such as manufacturing irregularities which existed before the pipeline was put into service or something attached to the pipeline are graded "U", for unclassified anomalies. The inspection procedure was carried out in such a way as to detect generalized pitting corrosion, both external and internal.

The pipeline system under consideration was divided into three regions. Table VII shows these regions, their lengths and the distribution of defect sizes. This distribution must be expressed as a probability density function. Since the number of anomalies decreases as the size increases, an exponential function is a candidate expression. However, it has infinity as its upper bound which is certainly beyond physical reality. A Beta density function was chosen as it can take an exponential form while having finite lower and upper bounds. It is given as:

$$f(x) = \frac{\Gamma(\eta+\gamma)}{\Gamma(\eta)\,\Gamma(\gamma)} \frac{(x - x_L)^{\gamma-1} (x_u - x)^{\eta-1}}{(x_u - x_L)^{\eta+\gamma-1}} \qquad (28)$$

where X_u and X_L are the upper and lower bounds, respectively; Γ is the gamma function; and η and γ are the shape and scale parameters of the density function. The upper bound is chosen to be 7.1 mm, the pipe wall thickness, while the lower bound is taken to be 1.065 mm, the detection threshold.

The future form of $f_X(x)$, i.e., its transformation in time, is obtained as a function of the growth of the anomalies during service. Unfortunately, there is insufficient information to describe the growth kinetics of the anomalies in this specific metal/environment combination. However, published data in the literature [35] as reported by Nathan and Dubaney [36] indicates pit depth as proportional to the 0.2 to 0.7 power of exposure time, i.e.,

$$X(t) \propto t^{0.2 \text{ to } 0.7} \qquad (29)$$

or in general

$$X(t) = at^b \qquad (30)$$

where a and b are constants. For the corrosion system on hand the value of b is unknown. From the random nature of the pitting corrosion process, one can expect a range of values for b. Thus, for this analysis, b is taken to be a distributed variable, and as a first approximation is uniformly distributed with limits between 0 and 1, i.e.,

$$f_b(b) = \begin{cases} 1 ; & 0 < b < 1 \\ 0 ; & \text{otherwise} \end{cases} \tag{31}$$

The lower limit for b indicates no growth, a phenomenon describing the behavior of pits that become inactive after some time. The upper limit, on the other hand, describes a linear growth rate. The time of inspection was approximately ten years after the start of service. If x is the pit depth at the time of inspection, then equation (30) is:

$$x(t) = x_{10}\,(t/10)^b \quad ; \; t \geq 10 \tag{32}$$

From equation (31) and a transformation of variables in equation (30), gives:

$$f_{x|x_{10}} = \begin{cases} \dfrac{1}{x \ln(t/10)} & ; \; x_{10} \leq x \leq x_{10}^{\,t/10} \text{ and } t \geq 10 \end{cases} \tag{33}$$

Equation (33), for a Markov process from which the transition probabilities can be obtained, and for equation (28), which defines the initial state probabilities, are sufficient information to describe the time evolution of the pit depth distribution.

In the numerical evaluation, the domain of the pit depths is discretized into small intervals of length Δx (here, Δx = 0.06035 mm, representing 1% of the significant range of the pit depth). The number of intervals used is sufficiently large to cover the significant range of the pit depth. Figure 14 shows the states of the pit depth at t = 10 years and at t = 10 + τ years, where τ is an increment of time. Initial and final state probabilities can now be defined as follows:

$$\begin{aligned} \text{(initial)} \quad & P_i^{\cdot} = P[X_{10} = i] = P[(i-1/2)\,\Delta x \leq x_{10} < (i+1/2)\Delta x] \\ \text{(final)} \quad & P_j^{\cdot} = P[X_{10+\tau} = j] = P[(j-1/2)\,\Delta x < x_{10+\tau} < (j+1/2)\,\Delta x] \end{aligned} \tag{34}$$

Using these definitions, the transition probability can be defined as:

$$P_{ij}(t) = P[X_{10+t} = j \mid X_{10} = i]$$
$$= P[(j-1/2)\Delta X \leq x_{10+t} \leq (j+1/2)\Delta X \mid (i-1/2)\Delta x < X_{10} < (i+1/2)\Delta X] \quad (35)$$

This transition probability is obtained from equation (22) as follows:

$$P_{ij}(\tau) = \int_{(j-i-\frac{1}{2})}^{(j-i+\frac{1}{2})} f_{X_{10+\tau} \mid X_{10}} \, dx_{10+\tau} \qquad \begin{matrix} j \, j \geq i \\ \tau \geq 0 \end{matrix} \quad (36)$$

The initial state probabilities, P_i, are calculated by integrating equation (28) for all i's. Now, equation (12) can be used to predict the transformation of $f_X(x)$ and this is expressed in terms of P_j. Given that only one inspection will be performed during the remaining design life (assumed to be 30 years), say t years after, the probability of failure during this period is calculated as:

$$P_{f_1} = 1 - \sum_{j=1}^{i_f - 1} P_j(\tau) \quad (37)$$

where i_f identifies the state of the wall thickness. Inspection of the system is unlikely to be perfect as there will be some probability that a defect, no matter how large, will escape detection and will not be repaired. This probability can be expressed as:

$$g(x) = 1 - C[1-EXP(-b(x-x_{th}))] \quad (38)$$

where

C = a constant slightly lower than 1, to indicate that even large defects do not have 100% detection probability.

b = a parameter to be determined, requiring that the probability of detecting a specified defect size equal a fixed value.

x_{th} = lower limit of detection

Equation (38) is given by Davidson (17). In this analysis C is taken to be 0.98, x_{th} = 1.065 mm and b = 0.58, evaluated by specifying the probability of detecting a defect equal to the wall thickness as equal 95%. A graph of this function is shown in Figure 15.

At any inspection time, for such a system, it is unrealistic to repair all the detected defects but rather only those defects exceeding a certain size. In this case, the repair size is assumed to be 4.97 mm (70% of wall thickness). For the analysis, it is assumed that the defects are repaired as good as new and the defects causing a leak are removed by replacement of a brand new pipe. This removes these defects from the original population. Of the remaining population, a fraction of these will fail by the end of service life. This second probability of failure is calculated as follows: from the calculated $P_j(\ )$ in equation (37), define a new set of P_i's, i.e.,

$$P_i = \begin{cases} P_j(t) & ; j < i_R \\ P_j(t)\, g((j-1/2)\Delta X) & ; j > i_R \end{cases} \qquad (39)$$

where i_R identifies the state of the repair size and $g((j-1/2)\Delta X)$ represent the probability of non-detection at the midpoint of the j-th state. Again, apply equation (12), but now using equations (36) and (39) to calculate the P_i's by the end of the design life. The second probability of failure is calculated as:

$$P_{f_2} = 1 - \sum_{j=1}^{i_d-1} P_j(30-t) \qquad (40)$$

The over-all probability of failure for the region with one in-service inspection is given by:

$$P_{f_T} = 1 - (1-P_{f_1})(1-P_{f_2}) \qquad (41)$$

and for the entire system is given by equation (19).

To benefit from the actual inspection, the probabilities of failure were calculated on the assumption that the original population of defects whose size exceeds 20% of wall thickness were repaired, hence, eliminated from the population. The resulting failure predictions give the probability of having a leak per kilometer of pipe over a 30-year period. These were transformed into number of leaks per thousand kilometers of pipe per year. The figures 16, 17, and 18 provide their respective graphical representation. The result corresponding to the inspection time at zero refers to the case when an inspection and repair would follow immediately after the first inspection. Since the analysis covered a 30-year period, the results at the inspection time 30 years refer to the failure prediction without the benefit of inspection and repair during the remaining design life; these will be used as reference values in calculating the Factor of Improvement, defined in this case as the ratio of the predicted leak rate without any inspection and repair during the

remaining design life to the predicted leak rate with one or more inspection. For a single inspection of the overall system, a plot of the Factor of Improvement is shown in Figure 19. It can be seen that even a single inspection during the remaining design life at the optimum time can improve the overall system's performance up to a factor of 4.6.

4.2 Suction Press Rolls

A simple representation of the suction roll is that of a thin-walled tube with a complex stress distribution between the inside and outside surfaces due to the combined nature of the loading. The shell has a multiplicity of holes where the stress pattern is strongly influenced by neighboring holes. The stress field produced by the loading is biaxial, consisting of longitudinal components resulting from beam bending and circumferential components resulting from ring bending. The suction hole pattern induces stress concentrations upon the biaxial stress field (local stress peaks appear (37)). As the suction roll rotates, the stresses at any one point undergo repeated reversal from tension to compression. The determination of the value of alternating stress requires that the maximum and minimum stress value at a particular point be determined as the roll rotates. The maximum and minimum stresses occur at the hole boundaries and are given by Mockaitis(38) combining photoelastic test data with the calculated stresses. The stresses at the hole boundary are either tensile or compressive and are tangent to the hole varying around circumference.

In the past, rotating components were designed to operate at stress levels not exceeding the material's "endurance limit". But many investigations and tests indicated that materials operating under corrosive conditions have no endurance limit (39 -41). Data on the corrosion fatigue strength of alloys is vital to the prediction of roll performance.

Corrosion fatigue is a combination of cyclic stresses and a corrosive (water solution) environment. No metal or alloy is immune to some reduction of its resistance to cyclic stressing if it is corroded by the environment in which it is stressed. The damage from corrosion fatigue is greater than the sum of the damage arising from cyclic stresses and that due to corrosion. Corrosion fatigue and air fatigue are fundamentally the same. They both are failures which proceed by initiation and propagation of a crack. However, the difference is that the rather corrosive aqueous environment of the press section of a paper machine reduces the stress that can be tolerated.

The number of failures of suction roll shells has not been published. It is known that many of the CA-15 alloy rolls have broken and a smaller number of the "300" and "400" series stainless shells have also fractured. The mode of suction roll

shell fracture has been identified as corrosion fatigue by several researchers (37-47). In order to successfully combat these failures, an understanding of corrosion fatigue is of paramount importance.

Failures have been observed previously on press shells fabricated from martensitic stainless steel alloys. Originally the shells were forged from resulfurized 410 steel. The hot working led to elongated MnS inclusions. These inclusions along with retained δ-ferrite acted as an origin of the cracking. The technology progressed to cast shells using the CA-15 alloy. Where the δ-ferrite, chromium carbides and MnS were all detrimental. More austenitic stainless steels have been used in recent years and fracture and corrosion seems to have become worse.

The origin of the cracking phenomenon is manyfold in terms of the overall ensemble of failures. The presence of metallurgical discontinuities such as inclusions, sigma and carbide phase and delta ferrite have been associated with the crack initiation phenomenon. In other cases, pitting corrosion with or without apparent resinous deposits have clearly initiated cracks. Mechanical damage due to high-pressure water jets used for cleaning the rolls and surface roughness in the as-drilled holes are also potential crack initiators.

Of course, crack initiation and propagation susceptibility are functions as well of the material properties including grain size. In martensitic shells, metal loss at the origin of cracks was identified with inclusions, excessive ferrite, pitting and mechanical damage. While the propagation modes do vary over the ensemble of failures, there is a greater incidence of fatigue toward the origin with brittle fracture occuring toward the end. There is a tendency for multiple initiations to take place at the beginning of the cracking process. There may also be some treeing or branching.

It has been recognized that the failure of suction roll shells is caused by corrosion-fatigue. There are two physical modes of suction roll shell service failures. The first-one, which is also most predominant, is the one where the crack propagates circumferentially. This type of crack usually appears near the middle length - of the shell and is caused by the stress in the axial direction. We will refer to it as Mode 1 failure. The second mode of failure is where the crack propagates initially in the longitudinal direction. This type of crack eventually changes direction by about 90 and the terminal crack is directed in the circumferential direction. This type of failure mode is a result of the stress in the circumferential or hoop direction. This type of failure will be referred to as Mode 2 failure.

From the past experience, it is known that most of the suction roll shell service failures are of Mode 1; which is caused by the stresses in the axial or longitudinal direction.

The crack spreads out in both directions from a hole in which it initiates. It propagates in a direction perpendicular to the plane of maximum normal stress. In most rolls this is a circumferential crack propagation direction. (In cases where the tangential stress predominates longitudinal cracks have been observed).

The cracks are usually in the center third of the roll or, more generally within 18" of the center of the roll. In cases where the roll cracked off-center, the plane of maximum bending stress was likewise off-center. Thus the failure most likely occurs close to the plane of maximum bending stress, unless the metallurgical or physical discontinuity responsible for initiation can concentrate stress sufficiently to initiate cracking at lower bending stresses.

The analytical techniques employed for attempting to predict suction roll life based on calculated stress levels have not enjoyed overwhelming success in the past, as evidenced by continuing failures in the field.

Many studies have been made to evaluate and to analyze aspects of the fracture mode and, until recently, almost all of this research effort has been performed by the machinery builders and

foundries which produces these giant centrifugal castings, the suction press rolls. The results of these investigations certainly have led to a better understanding of the suction roll fracture problem and have been used to provide guidelines for papermakers in the procurement and maintenance program of the suction rolls.

A model for the estimation of the life expectancy of the suction roll with crack-like imperfections should be based on probabilistic defect analysis and admit randomness in controlling input parameters such as material properties, loading stress, and defect distribution, rather than as single-point mean or "worst-case" values. The model and the methodology should be implementable for a great variety of analyses including design, material selection, stress levels, and in this report, the statistical approach is applied to the analysis of failure in suction press roll subject to several competing or complementary deterioration modes.

Through common usage, the corrosion fatigue strength of a metal is defined as the maximum repeated stress cycling that will not cause failure in a stated number of stress applications under defined conditions of corrosion and stress range. The value is significant only when the conditions are completely defined. Time and rate of stress applications have much greater importance than in air fatigue. Depending upon the basis chosen, a metal may have numerous corrosion fatigue limits. Other factors which exert a marked influence on the corrosion fatigue limit are the nature of the corroding medium, nature and range of stress, rate of stressing, temperature and inherent corrosion resistance of the metal.

To gain more insight and understanding of the failure mechanism, one must not overlook the microscopic processes leading to shell failure. The study of the shells that failed is essential, with special attention paid to the microstructure of the materials in question.

Upon examination of a stainless steel suction roll shell which has been in service for some time, the first thing one would notice is the number of pits, scattered at random on the inside surface of the shell. The same corrosion pits can also be found on the inside of the holes of all broken shells.

The corrosion pits not only reduce the volume of the material, but also produce stess raisers, along with a very active electrolytic cell which will further accelerate pit growth (37).

Another important observation (45) is that casting defects such as voids and flaws inevitable in castings structures may accelerate the fatigue crack nucleation step. From a number of failed suction press rolls it was also observed that, out of 6 rolls, in 5 the origin of the fracture was a casting defect and only 1 in 6 was a corrosion pit.

Qualitative Model

The suction rolls are thin-walled, freely supported beams with a linear load distribution. Due to the drilling pattern as is shown in Figure 20 the stress pattern is very erratic and high stress concentrations are experienced. When this is combined with the application of a cyclic load (inherent in a rotating component), the result is a very complex stress pattern.

The representative dimensions of the typical suction roll are 38 in. O.D., 34 in. I.D. and 227 in. long. The drilled holes are approximatively 3/16 in. in diameter with 0.28 to 0.46 in. between the holes.

The so-called "White Water", the operating fluid in the paper-making operation, provides a corrosive environment which operates on the stainless steel from which the roll is made.

There is some evidence that brittle fracture precedes the ultimate failure which is determined by excessive roll deflection due to loss of section rigidity in the presence of an extended crack.

The structural reliability of suction press rolls and other load-bearing structures depend on parameters such as stress and residual strength, pre-existing cracks and crack-like flaws which are subject to both random and systematic variations.

One method to determine reliability simply extrapolates from past failure data and experience, and ignores many explicit physical details of the system. This "Database" approach to evaluate reliability is relatively straightforward and, given a large enough base of relevant data, a direct relationship with actual field experience does not require the use of analytical models or laboratory tests.

The disadvantage of such an approach is that the capability to predict the effects of systematic changes in key parameters is severely limited, since adequate data on the effect of such changes normally do not exist. A second approach to the prediction and improvement of reliability involves the development and application of engineering models based on an understanding of the failure modes and the statistical distributions of the controlling parameters.

This approach to the prediction of reliability analyses failure is from the "inside" of the component or system. The key-stone of

the approach is a deterministic engineering model of one or more system failure modes. The physical model can be based on fracture mechanics analysis, fatigue life analyses, or some other relevant form of stress analysis combined with material characteristics. The approach combines known, assumed, or proposed statistical variations of controlling parameters, expressed as cumulative probability distribution function (PDF), to predict statistical variations in structural performance through the deterministic engineering model.

Failure in the suction press roll is a multimode phenomenon involving essentially two stages. Each of these stages can involve one or more steps, generally initiation and propagation. Characteristic mechanisms associated with each phase are:

for stage I - corrosion-fatigue
for stage II - fracture

The relative importance of each stage and of the steps within a stage are material dependent and depend as well as the loading conditions.

Loading conditions require characterization of the nominal stress field, stress concentration and stress intensity factors. Stages I and II are essentially sequential at a given point in the roll. However, due to the statistical variations in the initial manufacturing defects and in the material properties which govern the crack initialization and development, several networks will develop in parallel and exist at varying stages of development.

Since failure occurs when overall cracking throughout the roll reduces integrity and thus the rigidity to the point where the structure can no longer operate, it is necessary that the comprehensive failure model incorporate the statistical development of the complete fracture map.

Metallurgical observations of failed rolls provides the key to modelling. Thus, the first of the input options to be selected for analysis will be the manufacturing defects resulting from casting. There is strong evidence that the material is not always perfect, nor is the fabrication processes to which it is subjected. The level of strength of a suction press roll material can be considerably reduced by the introduction of a "weak spot". These weak spots formed after casting may take various forms such as inclusions of a foreign material, porosity, voids or other physical irregularities. While some may be classed as quality defects, they may not all be detectable by known control processes. Experimental observations showed in a number of cases that crack initiation tends to occur at stress raisers produced by casting defects at corners of holes and within the first third of the wall thickness. Most fractured lands have markings which indicate origin on inside diameter of the shell with propagation to the outside diameter. The fractured land show that the origin of crack is in one of these casting defects which reaches the

surface or the peripheries of the holes. Therefore, only those casting defects which reach the surface, are important from point of view of their potential to initiate a corrosion-fatigue crack. In order to find the relationship between the size and intensity (number) as well as their location of surface-casting defects and the probable number of fatigue crack initiations, we need the distribution of these defects expressed in terms of number per unit area.

The unit area will be represented by 1/3 of the surface of drilled hole situated at bottom, near the inner shell surface. Therefore, given the information about the as-fabricated casting defects measured by destructive testing and the information about their severity, there is the possibility to obtain the distribution of these defects. This first stage of analysis can be divided into the following important steps:

a) Express the measured data relating with casting defects into a histogram form.
b) Fit an appropriate distribution function and establish the limits of this distribution.

The second stage which is extremely important in this analysis is the relationship between the surface-casting defects responsible for the crack (starting) initiation sites and the physical process of fatigue crackinitiation itself, represented graphically by S-N curves (Wohler diagram). In fact, it has long been known that fatigue usually initiates at a surface because stresses are normally higher there, particularly since most parts experience bending loads resulting in substantially higher stresses in the outermost fibres. Stress-concentrations resulting from local surface defects are occasionally as effective in reducing the fatigue life of structural parts as are large scale stress concentrations resulting from design deficiencies.

Ever since the beginning of fatigue endurancetesting, S-N curves have been the backbone of fatigue data: S denotes stress amplitude of the maximum cyclic stress, and N denotes the number of cycles to complete fracture. The linear S versus log N scale is the most common and is used almost exclusively in engineering. Typical S-N curves are shown in Figure 21 from [48] for rotating bending at different frequencies for a stainless steel material Suppose that the equation describing these S-N curves is given by the formula [46].

$$N = B.f. \exp(aS) \qquad (42)$$

where N is the number of cycles to initiate a fatigue crack, f is frequency in hertz, S is the stress in KSI, B and a are constants specific for the material, and the conditions of the experiment.

The values of these constants for KSR-171 material are:

$$B = 1.79 \times 10^{-7}$$
$$a = -0.17 \quad (-0.2465)$$

The value of the stress S in the above formula, which is the stress at the root of notch in this case the surface casting defects may be calculated using the formula [49]

$$S = S\ (1 + 2\sqrt{\frac{l}{r}}) \qquad (43)$$

where S is the stress corresponding to the (flawless) specimen, l is the depth of surface defect, and r is notch radius. Therefore, there is a close relationship between the stress value and the existence of casting defects, random in size and number; this leads to the idea that the spread in the useful life of the structure is caused by the number and size of these surface casting defects. Consequently, in principle, it is possible to build, by simulation, the S-N curves in which the value of the stress is a random variable, because the principal parameter, the depth of casting defect, which enters into its calculation are euezom. The resulting S-N curves will be a kind of P-S-N curve (probabilistic S-N curves) which would have the capability to predict, for example, the chances to have a useful life exceeding 10^8 cycles given a certain distribution of casting defects.

Two levels of modelling are required in order to develop the complete failure model:

Level I: Initiation
Level II: Propagation

LEVEL I ANALYSIS

The crack initiation phase includes both microcrack initiation and early macrocrack growth. At the end of this phase a crack of very small but finite size exists. The duration of initiation phase is influenced by a number of variables which has been mentioned before, but briefly we remember only the depth of casting defects and the effect of these on applied stress. Using a deterministic relation between stress and geometrical characteristics of casting defect which is interpreted as a notch, an attempt has been made

to express the variability in stress magnification by the variability in notch size and radius.

Thus given the relation established by INGLIS [49]

$$S = S_0\left(1 + 2\sqrt{\frac{l}{r}}\right) \tag{44}$$

where S = maximum stress at the end of major axis
S_0 = applied stress normal to the major axis
l = half major axis (depth of defect)
r = the radius of curvature at the end of the ellipse given by:

$$r = \frac{l^2}{a} \tag{45}$$

where a = half minor axis

In the most cases a>>r, and therefore,

$$S \approx 2S_0\sqrt{\frac{l}{r}} \tag{46}$$

the term $2\sqrt{\frac{l}{r}}$ is defined as the stress concentration factor k_t and describes the effect of defect geometry on the local crack tip stress level. Although the exact formulations vary from one case to another they all reflect the fact that k_t, increases with increasing in defect depth and decreasing defect radius. Expressing now the depth of defect as a function of stress and curvature radius we have:

$$l = \frac{r}{4S_0^2}S^2 \tag{47}$$

and deriving relative to S both terms

$$\frac{dl}{dS} = \frac{r}{2S_0^2}S \tag{48}$$

Using now the probabilistic transformation of variable we get:

$$f_S(S) = \left|\frac{dl}{dS}\right| f_l(l) \tag{49}$$

or replacing l with its equivalent:

$$f_S(S) = \frac{r}{2S_0^2}S f_l\left(\frac{r}{4S_0^2}S^2\right) \tag{50}$$

where $f_S(S)$ is the maximum stress density function at the tip of the notch, $f_l(l)$ is the density function of casting defects size (one dimension size, depth).

Step 2: Once the distribution of maximum stress $f_S(S)$ being determined and knowing the deterministic relation between the maximum stress S and number of cycles at initiation N given by equation:

$$N = B\,\gamma\, e^{(aS)} \tag{51}$$

we can obtain the distribution of number of cycles at failure or the distribution of the initiation time.

Expressing as before the maximum stress S as a function of N

$$S = \frac{1}{a} \ln\left(\frac{N}{B\gamma}\right) \tag{52}$$

and finding the derivative of S relative to N as:

$$\frac{dS}{dN} = \frac{1}{Na} \tag{53}$$

we can express using the same probabilistic transformation technique:

$$f_N(N) = \left|\frac{dS}{dN}\right| \cdot f_S(S) \tag{54}$$

which became by the value of S and $\left|\frac{dS}{dN}\right|$

$$f_N(N) = \frac{1}{Na} f_S\left[\frac{1}{a} \ln\left(\frac{N}{B\gamma}\right)\right] \tag{55}$$

This can be interpreted as the distribution of the number of cycles to initiate a propagting corrosion fatigue crack.

LEVEL II ANALYSIS

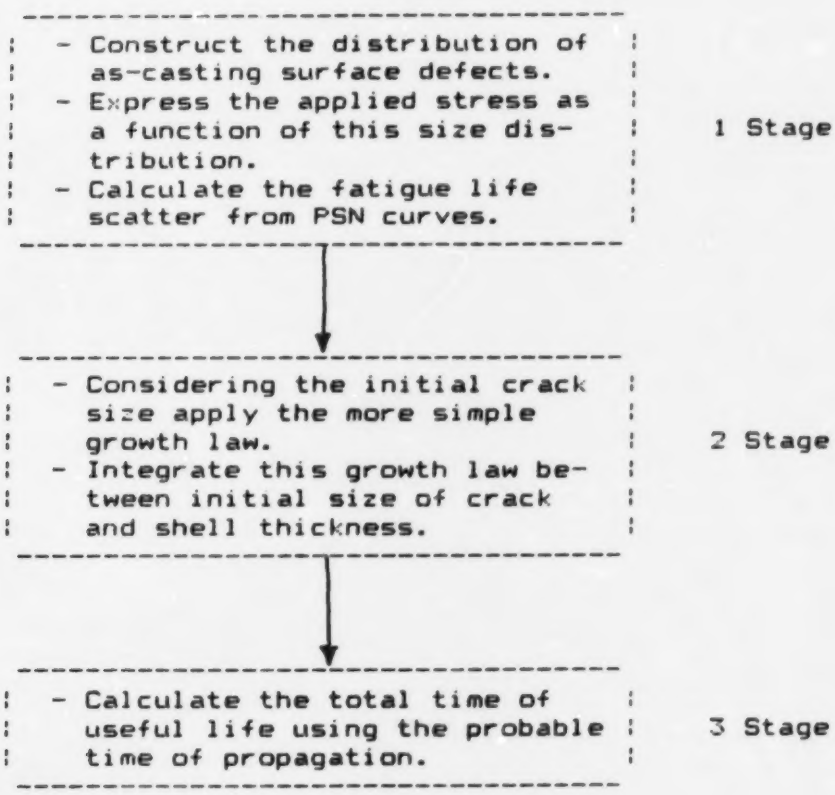
So far, only the initiation time t can be obtained by establishing the distribution of surface casting defects and by constructing the probability-stress-life curves. But to obtain

the total corrosion-fatigue life we need the propagation time t which can be derived from the distribution of fatigue cracks and the propagation law applied to them. Using the experimental informa- tion about the fracture mechanic parameters, material properties, failure criteria it is possible to determine the propagation time.

Thus:

Useful life = initiation time + propagation time

Now, we can outline the general approach applied into this analysis by using the systems methodology as following:


- Construct the distribution of as-casting surface defects.
- Express the applied stress as a function of this size distribution.
- Calculate the fatigue life scatter from PSN curves.
1 Stage
- Considering the initial crack size apply the more simple growth law.
- Integrate this growth law between initial size of crack and shell thickness.
2 Stage
- Calculate the total time of useful life using the probable time of propagation.
3 Stage

The total useful time can be expressed as

$$T = t_i + t_p \qquad (56)$$

and because either t_i or t_p, or both, are probabilistic, or T will be expressed as a distributed value.

5. TECHNICAL DISCUSSION

With the information provided in the previous pages it is possible to effect a multiparameter analysis which considers the complex problem of failure in suction press rolls. The modeling has defined the structure of the problem. In effect the analysis carried out herein involves only the degradation block, its inputs and outputs. Potential outputs from the analysis could have comprised time to fatigue crack initiation and propagation. In order to derive this output, several types of data are required as inputs.

In general all the data of concern are obtained by three approaches:

1) Review of past experience based on:
   a) Analysis of metallurgical reports of failure
   b) A review of operation maintenance records

2) Detailed engineering analysis to determine failure modes based on studies of fabrication methods and operational and maintenance procedures.

3) In service evaluation of specific components or simulation test specimens, operating in the actual plant environment.

The results of these approaches are to be integrated into a specific format into a total failure analysis program. Failure history data bases provide one of the principal sources to identify the elements and procedures involved in suction press roll failures that can cause outage or safety-related incidents in paper mills. Only from this source we can obtain information on:

1) The frequency and severity
2) Whether a particular failure is part of a generic class or an isolated event
3) Root cause of failure.

The information obtained from analysis of past experience is used to identify elements which are potentially responsible for failure and which should be subjected to detailed engineering failure analysis. To perform the structural and mechanical analysis it is necessary to define the geometrical form of the structure, the actual mechanical, chemical and other environment forces acting on the structure and to isolate the degree to which these forces can be monitored and controlled.
For example, the above requirements involve the collection of design, laboratory test, and operational data on component environment, and the reduction of the loading data to forms that can be easily implemented for the deterministic or probabilistic fracture mechanics analyses and life time predictions. Since the structural and mechanical analysis defines the resistance of materials to forces imposed on them, it is necessary to know

pertinent material properties and the statistical variation of these properties due to uncertainty in testing method and general quality control. Moreover, the magnitude of the alternating stress and residual stresses in different locations of the structure and effect of the aggressive environment on material properties must also be defined.

It is necessary in certain cases such as the suction press roll to set up laboratory test conditions that can adequately model the operating environment to extract pertinent information at reasonable levels of confidence.

Geometrical parameters:

- length of the shell
- outer diameters
- inner diameter
- hole diameter
- space between holes { axial / tangential }

Physical parameters:

- material density
- angular velocity
- Young's modulus
- roll velocity

Metallurgical parameters:

- uniform load
- dead weight
- fracture toughness
- load application zone
- alternating stress
- maximum stress
- stress concentration factors

The following parameters can be determined with a relatively high degree of certainty. They include:

- length of the shell
- outside diameter
- thickness of the shell
- hole diameter
- space between holes-axial and tangential
- material density
- gravitational acceleration
- roll velocity
- Young's modulus
- uniform load
- dead weight

Derived parameters which can be established through advanced computational techniques with reasonable certainty include:

- alternating stress
- maximum stress
- stress concentration factors

Several logic modeling also suggests that the stress analysis be able to compute roll rigidity as a function of crack size.

The next set of data required may be considered as materials-related or metallurgical. The uncertainty associated with these properties considerably exceeds that of the conventional data with possible exception of the cyclic loading spectrum. Materials-related data include:

- initial casting surface-defect size
- number of such defects per unit area
- fracture toughness
- initial crack size for fatigue process
- threshold stress intensity factor
- fatigue crack growth parameter C
- fatigue crack growth parameter m

While these are well known as key parameters and such data are or will be generated in research programs, the experiments should be set up to extract the information in a statistical format. Thus each of the above metallurgical parameters should be determined with sufficient tests to evaluate the location parameter and the scale parameter for the appropriate distribution. Similarly, any fracture, fatigue or corrosion test should provide data to determine the best distribution function to describe its statistical variation. Since it is normal experimental practice to obtain this type of data through several replications of the test, it remains simply to assure that these replications are designed to extract the required statistical information.

It is evident that certain of the materials-related data can be obtained through laboratory testing. In fact a complete baseline data set can be established through a testing program. This data set can be used to evaluate candidate materials and to optimize materials selection. Likewise any field information on crack growth rates would be used for comparison with the baseline data.

6. CONCLUSIONS

Systems analysis principles provide a complementary approach to failure control problems in load-bearing structures subject to materials degradation. They provide a simple description of information flows in which the tools of operations research, materials science, mechanics and reliability engineering are combined. Their application to failure control problems structures the information content and information flow among disciplines contributing to the analysis. Significant improvements in reliability can be achieved by implementing these principles.

The most important outcome of this approach is what we have called the "probabilistic defect ananlysis" (PDA). Unfortunately, the art of achieving accurate analysis by using PDA without excessive and complex calculations is still in an early stage of development. However, a certain conceptual framework, and a number of theoretical procedures have emerged and various models of different complexities have been proposed. This report found that there is a certain commonality among the various approaches, which involves quantification of probabilities of initial defects, inspection uncertainty, flaw growth, fracture toughness and environment. Some considerations have already been given to the effect of using different statistical models to describe these controlling input factors. It is often impossible, if not very difficult, to decide which of several competing models provides the best prediction and the choice can have a profound effect on probability estimates particularly in the tails of the distributions. This effect must be clearly investigated if any reliability or safety analysis is to be performed to determine the susceptibility of results to the choice of the model and therefore to help estimate the accuracy of the predictions. There is very little information on key controlling factors in the open literature and to justify the assumptions made regarding the distribution type and shape it is necessary to carry out many sensitivity studies and laboratory and field tests.

As has been shown in this report, the concept that material degradation mechanisms can be modelled in terms of stochastic processes, in particular Markov processes, has very powerful and far reaching implications in terms of component and/or system reliability. In particular, pitting corrosion modelled in this way has led to definite predictions of a pipeline system's reliability but, of course, only time will tell if these predictions are indeed correct. Any marginal outcome will, however, not detract from the viewpoint that very impressive reliability estimates, inspection and repair recommended schedules and general levels of confidence can be attained by considering

time dependent degradation processes from this philosophical viewpoint. Indeed, all that remains is to determine the correct Markov law which describes a particular corrosion systems' time evolution.

A complete top-down systems analysis has led to the development of qualitative modeling of suction press rolls. The modeling exercise has identified the information required to describe the complete failure process and how the information will be combined quantitatively. To fully exploit and improve this model future work of three types can be envisaged:

Program development
Laboratory studies
Field studies

Program development:

To perform a life time evaluation of Suction Press Rolls the FRACTROL program should be extended to add new features as required by this specific problem.

Laboratory studies:

Experiments should be carried out to generate the data required for a baseline data bank on the basic suction roll candidate materials in model-compatible formats.

Field studies:

Wherever possible and perhaps as a cooperative industry-wide program field data should be generated on the corrosion and crack growth data specific to the service environment.

The modeling exercise itself has revealed several areas where work is required. One of these is the development of a flaw size distribution transformation law which admits of birth of defects. Further work is also required in the area of the inspection capability in characterizing the probability of nondetection using actual inspection data. In the latter regard, modeling of the uncertainty of inspection should be carried out to consider over- and underestimation of defect size with nondetection as a limiting case. For various industrial sectors, quantification of the model is required using data obtained under conditions reflecting current inspection practice. This will require that the model be developed to exploit field data as much as possible to minimize the amount of laboratory work and special sample preparation.

NOMENCLATURE

$PD(a)$	Flaw detection probability function
a	Flaw size
a_{th}	Threshold flaw size
a_{max}	Maximum flaw size
m	Empirical parameter
C_i	Constant
B_I	Constant
$f_c(x)$	Flaw size probability density function after inspection.
$PND(x)$	Flaw size non-detection probability function.
$f_t(x)$	Flaw size probability density function before inspection.
a_f	Failure flaw size
a_{tol}	Tolerable flaw size.
$f_{new}(x)$	Reconstructed flaw size probability density function.
$f_r(x)$	Repaired flaw size probability density function.
$f_o(x)$	Original flaw size probability density function
A,B	Constants
T	Time set
t	Point of time in the time set T

$X(t)$	Stochastic process (Random varible that describes the state of the Process at that point in time t)
$X_1(t_1), X_2(t_2) \ldots X_n(t_n)$	A set of n-jointly distributed random variables
$(x_1, x_2, \ldots\ldots x_n)$	The joint density function of random variables characterising a stochastic process.
$(x_n \mid x_{n-1} \ldots\ldots x_n)$	The conditional density function of x given the fact history of the process
$x_n, x_{n-1}, \ldots\ldots x$	States of the stochastic process. (values).
$f(x_n \mid x_{n-1})$	Transition density function of the Markov process, e.g., the probability of passing from a present state x_{n-1} to a future state x_n
$P(X_n = x_n \mid X_{n-1} = x_{n-1})$	Transition probability function correponding to the transition density function. (Discrete case)
$P(X_n \in E_n \mid X_{n-1} \in E_{n-1})$	Transition probability function general case.
E_n, E_{n-1}	Statistical events where the probabilities X_n, X_{n-1} are defined.
$\in$	The symbol may be read "is/are defined on"
$\mid$	The symbol may be read "given that"
$P_j(t)$	Absolute probability of being in state j after some time t.
$P_j(o)$	Absolute probability of being in the ith state at time t=o

TABLE III

Types of Flaw Size Distribution Used in Analysis

Distribution	Objective of Analysis	Reference	
Uniform	Fracture and fatigue reliability assessment of hulls	Lomacky et al	[7]
Exponential	Reliability assessment of pressure vessels	Becher and Pedersen	[8]
		Marshall et al	[9]
		Lidiard and Williams	[10]
		Harrop	[11]
		Jouris and Schaffer	[12]
		Botterill	[13]
		Johnston	[14]
		Marriott and Hudson	[15]
		Wellein and Schmitt	[16]
		Davidson	[17]
		Whittaker and Saunders	[18]
Gamma	Reliability calculation of pressure vessels	Nilsson	[19]

TABLE III (cont'd)

Types of Flaw Size Distribution Used in Analysis

Distribution	Objective of Analysis	Reference	
Beta	Inspection optimization by in-service inspection	Arnett	[20]
	Reliability calculation	Kitagawa	[21]
Log-normal	Reliability calculation of pressure vessels	Dufresne	[22]
	Effects of NDE and proof testing on the reliability	Harris	[23]
	Structural reliability calculation of turbine rotors	Besuner and Tetelman	[24]
	Reliability calculation	Jouris and Shaffer	[12]
	Probabilistic updating of flaw size distribution	Tang	[26]
Extreme-Value	Reliability estimation of pipeline	Finley	[27]
	Reliability estimation of offshore structure	Oswald and Schueller	[28]

TABLE IV

Estimated Number of Defects in Certain Structures such as Pressure Vessels and Primary Pipes

Number of defects per Vessel	Number of defects per cubic meter or linear meter	References and Authors	
1/vessel		Becher and Hansen	[28]
15/vessel with a radius greater than 5 mm	0.778 per meter of weld	Nilsson	[19]
0.018 or 0.05/vessel larger than 0.2 inches		Arnett	[20]
0.4/vessel		Vesely et al	[29]
3.6/vessel		Marshall	[9]
	0.854 to 3.36 per cubic meters	Harris	[23, 30, 31]
	0 - 50/weld	Dufresne et al	[22]

TABLE V. Pit growth laws

	LAW	APPLICATION	REFERENCE
(1)	$x(t) = a t^{1/3}$	aluminum	Godard [50]
(2)	$x(t) = b \log t + c$	pipelines	Finley [26]
(3)	$x(t)^{*} = a t^{b}$	buried pipe data	Crews [51]
(4)	$x(t) = x_f (1 - e^{-t/b})$	steel pipelines	Tsickerman [52]
(5)	$x(t)^{**} = \frac{x_f t}{a + t}$	steel pipelines	Tsickerman [52]

where x = pit depth

x_f = final pit depth

t = exposure time

a, b, c = constants

* This equation was inferred from the pit growth curves in Crews' [51] article.

** This equation is given by Tsickerman [52] as an approximate expression of equation (4).

TABLE VI. Transition Probabilities of Some Classical MARKOV PROCESSES

1) Poisson Process

$$P_{ij}(t) = \frac{(\lambda t)^{j-i} e^{-\lambda t}}{(j-i)!} \quad ; \quad j \geq i$$

2) Homogeneous linear birth process

$$P_{ij}(t) = \frac{(j-1)!}{(j-i)!(i-1)!} e^{-i\lambda t} (1 - e^{-\lambda t})^{j-i} \quad ; \quad j \geq i$$

where λ is a non-negative constant, t is the time interval and i and j identify the states.

TABLE VII. DISTRIBUTION OF DEFECTS

REGION	LENGTH (KM.)	NUMBER OF DEFECTS		
		> 1.065 mm	> 2.13 mm	> 3.55 mm
1	352	702	108	16
2	350	224	48	4
3	255	159	54	12

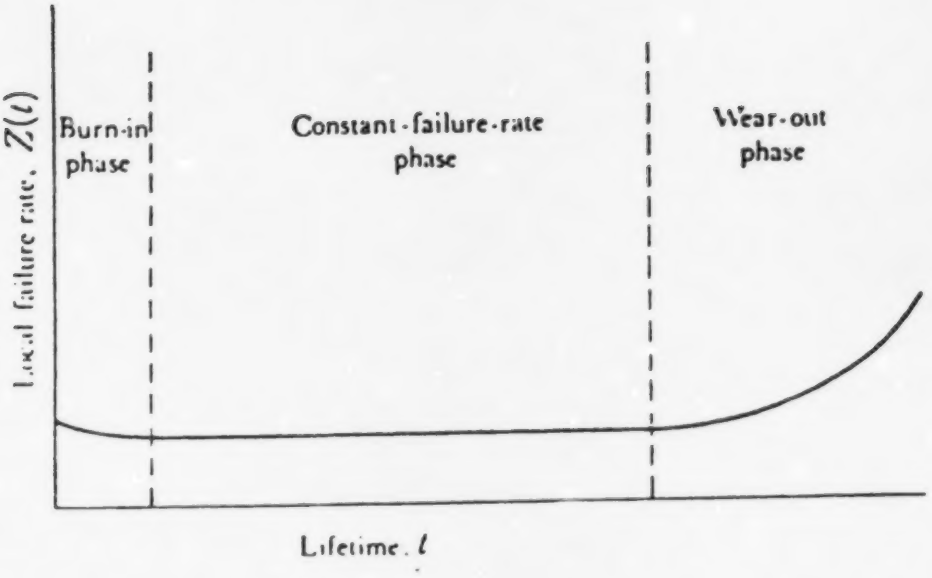


FIGURE 6. BATHTUB CURVE

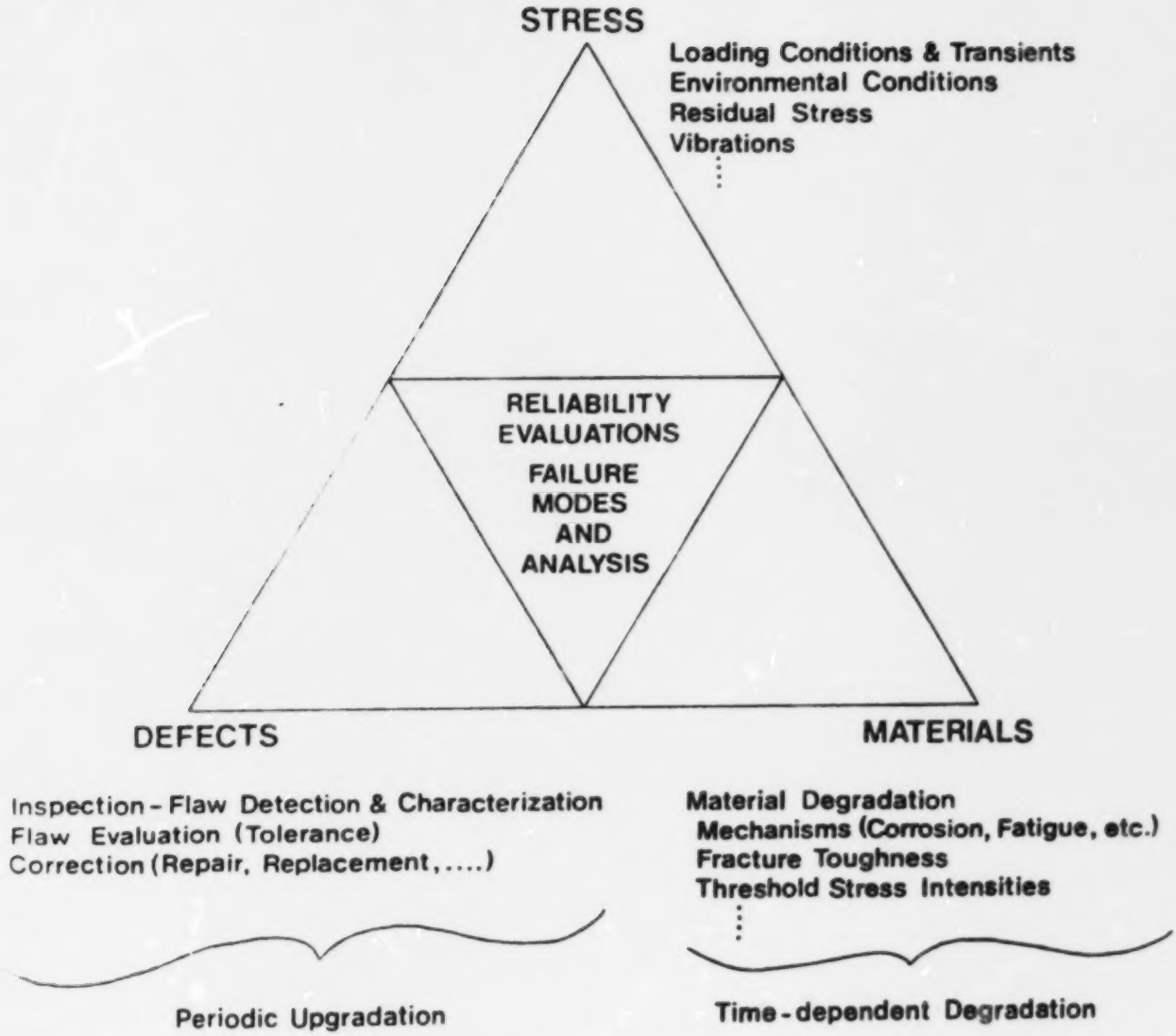


FIGURE 7. INFORMATION REQUIRED FOR A PROBABILISTIC DEFECT ANALYSIS

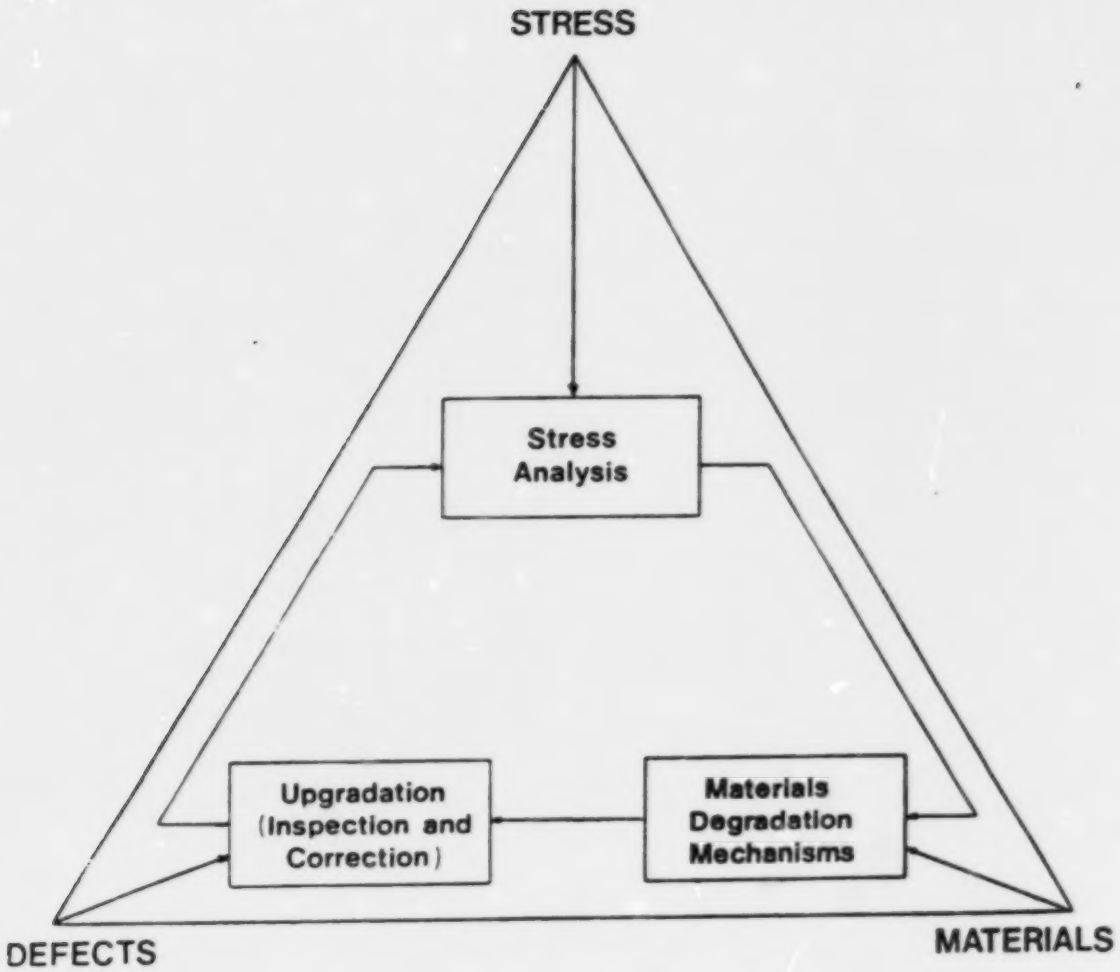


FIGURE 8. INFORMATION FLOW IN A PROBABLISTIC DEFECT ANALYSIS

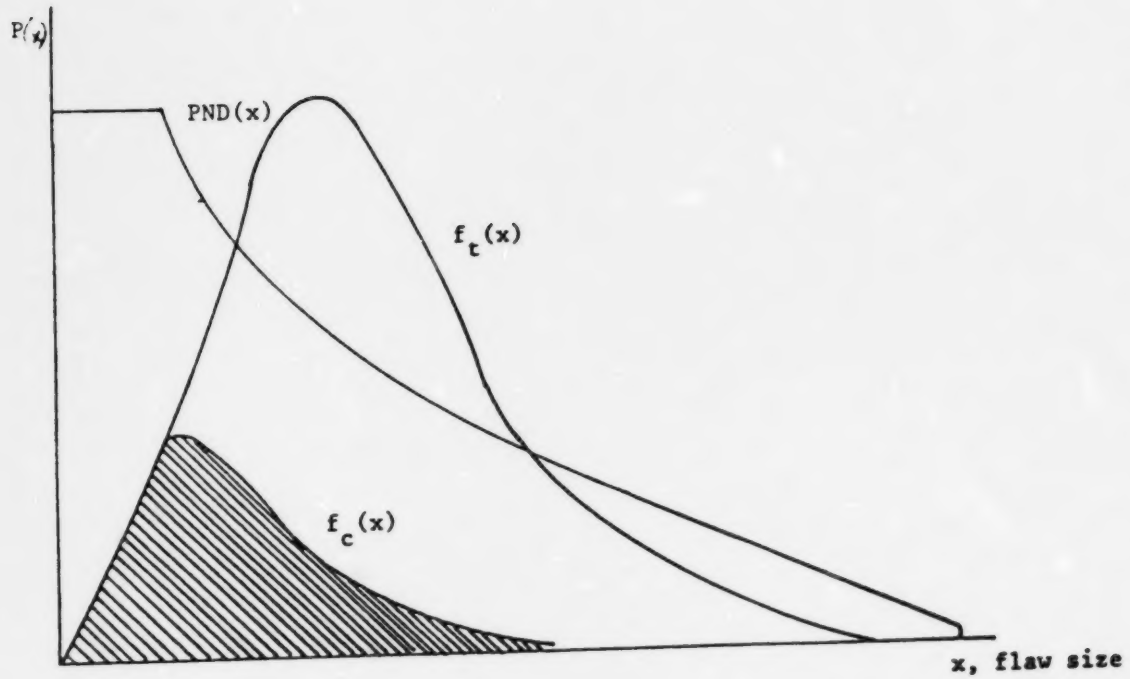


FIGURE 9. THE INSPECTION PROCESS

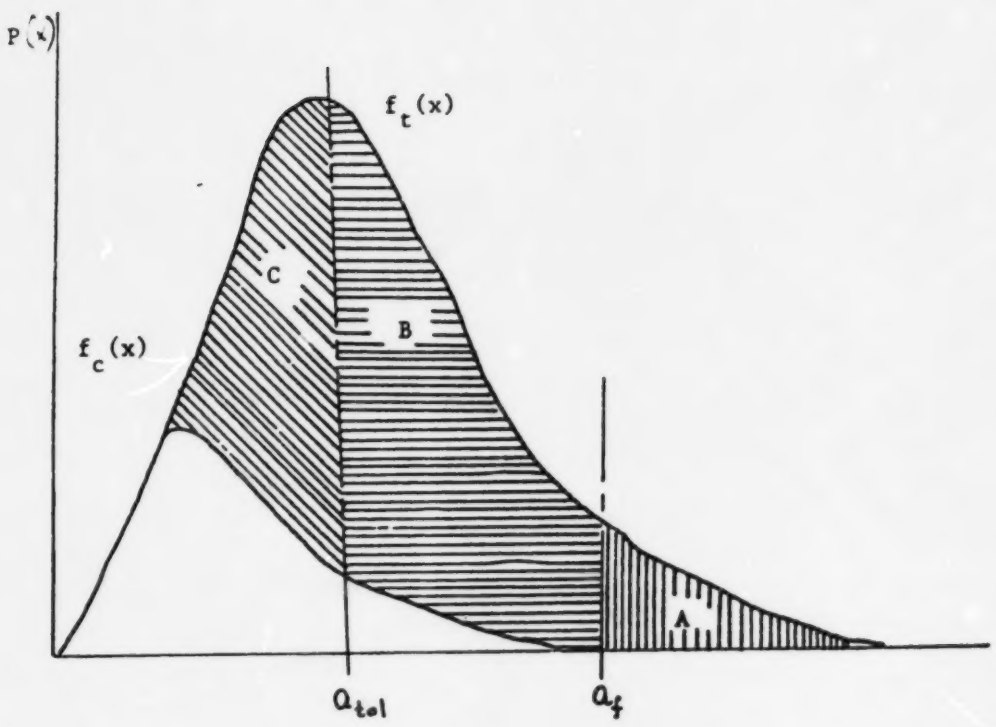


FIGURE 10. FRACTION OF THE POPULATION REPAIRED AND REPLACED

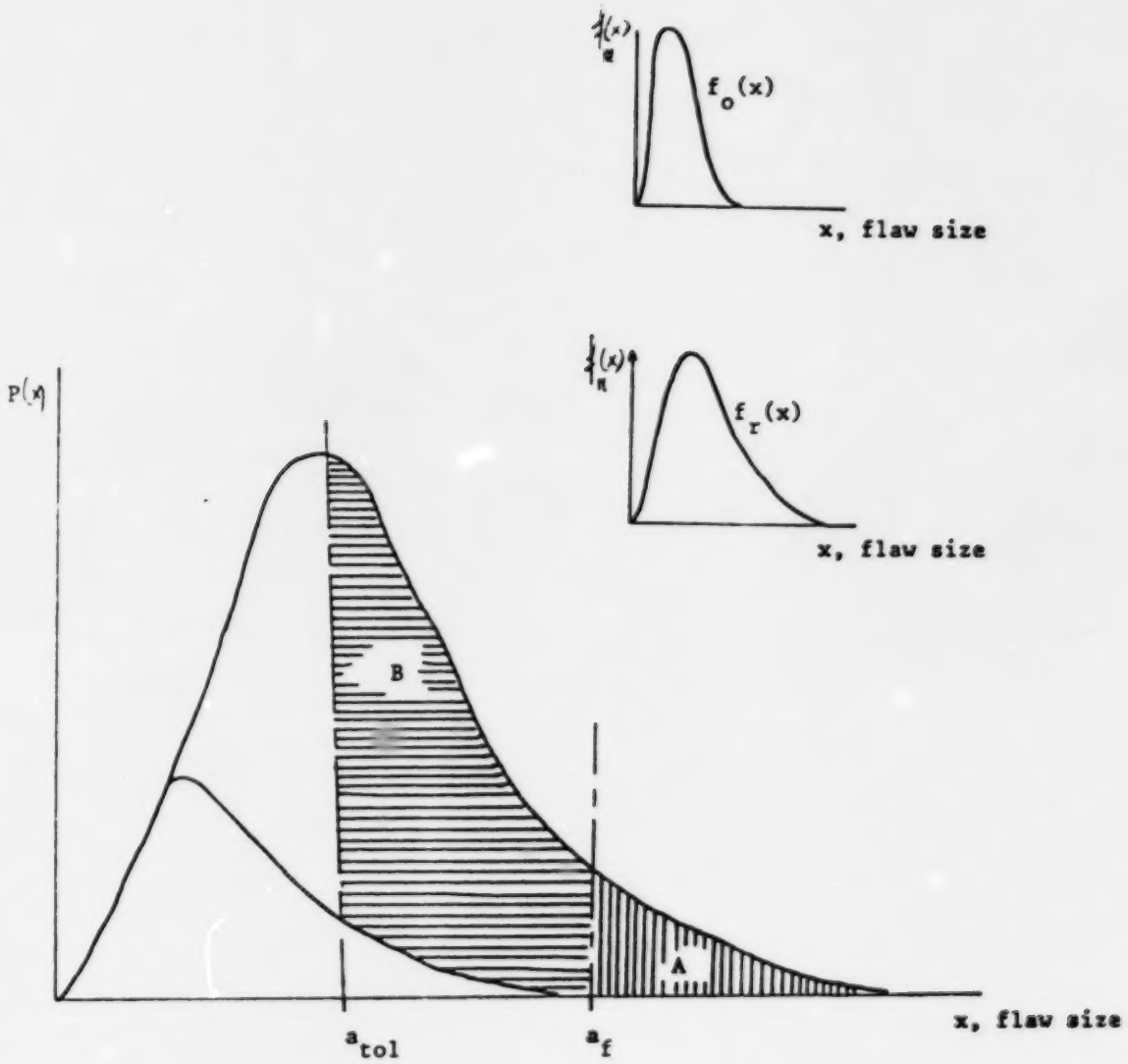


FIGURE 11. GRAPHICAL REPRESENTATION OF THE PARAMETERS REQUIRED TO RECONSTRUCT FLAW SIZE DISTRIBUTION DUE TO REPAIR AND REPLACEMENT.

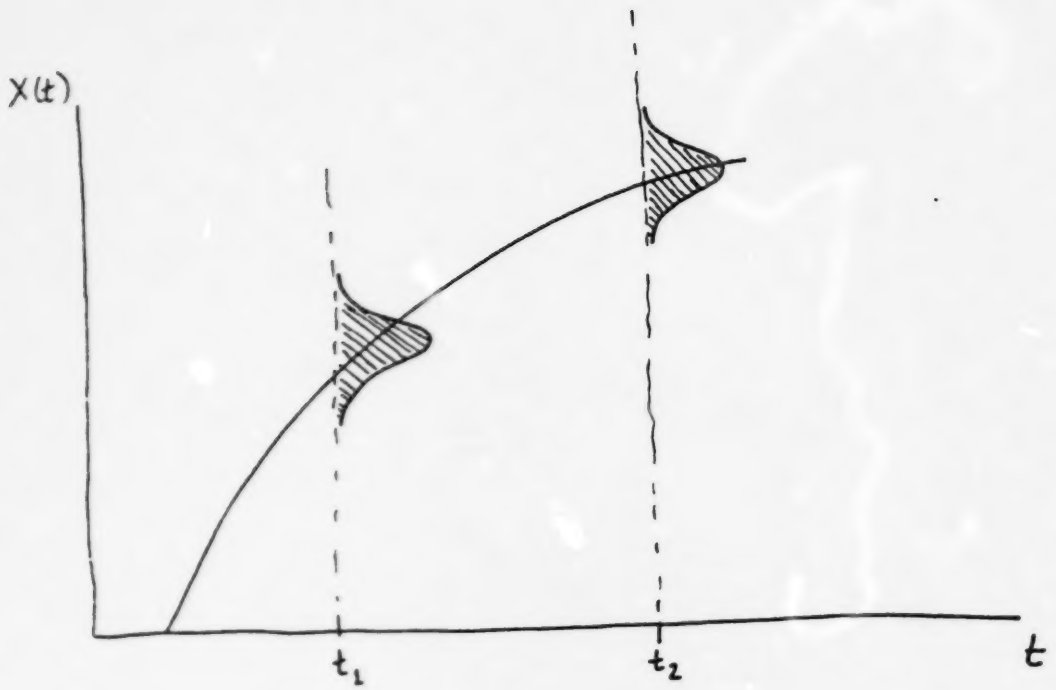


FIGURE 12. AVERAGE GROWTH OF A PIT SHOWING THE SCATTER AROUND THE MEAN AT TIMES t_1 AND t_2

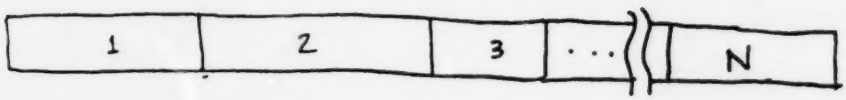


FIGURE 13. A PIPELINE SYSTEM DIVIDED INTO N REGIONS

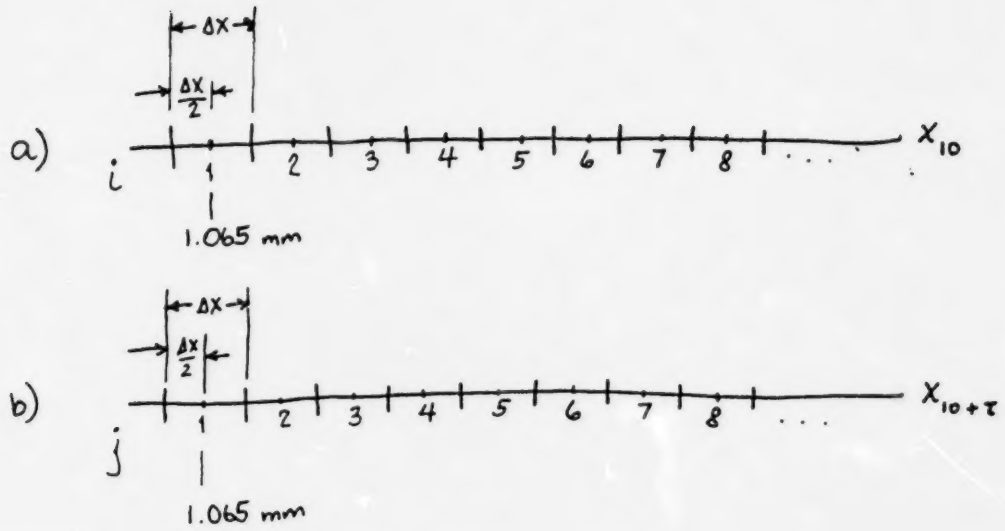


FIGURE 14. A) DISCRETIZED DOMAIN FO THE PIT DEPTH AT $t = 10$
B) DISCRETIZED DOMAIN OF THE PIT DEPTH AT $t = 10+\tau$

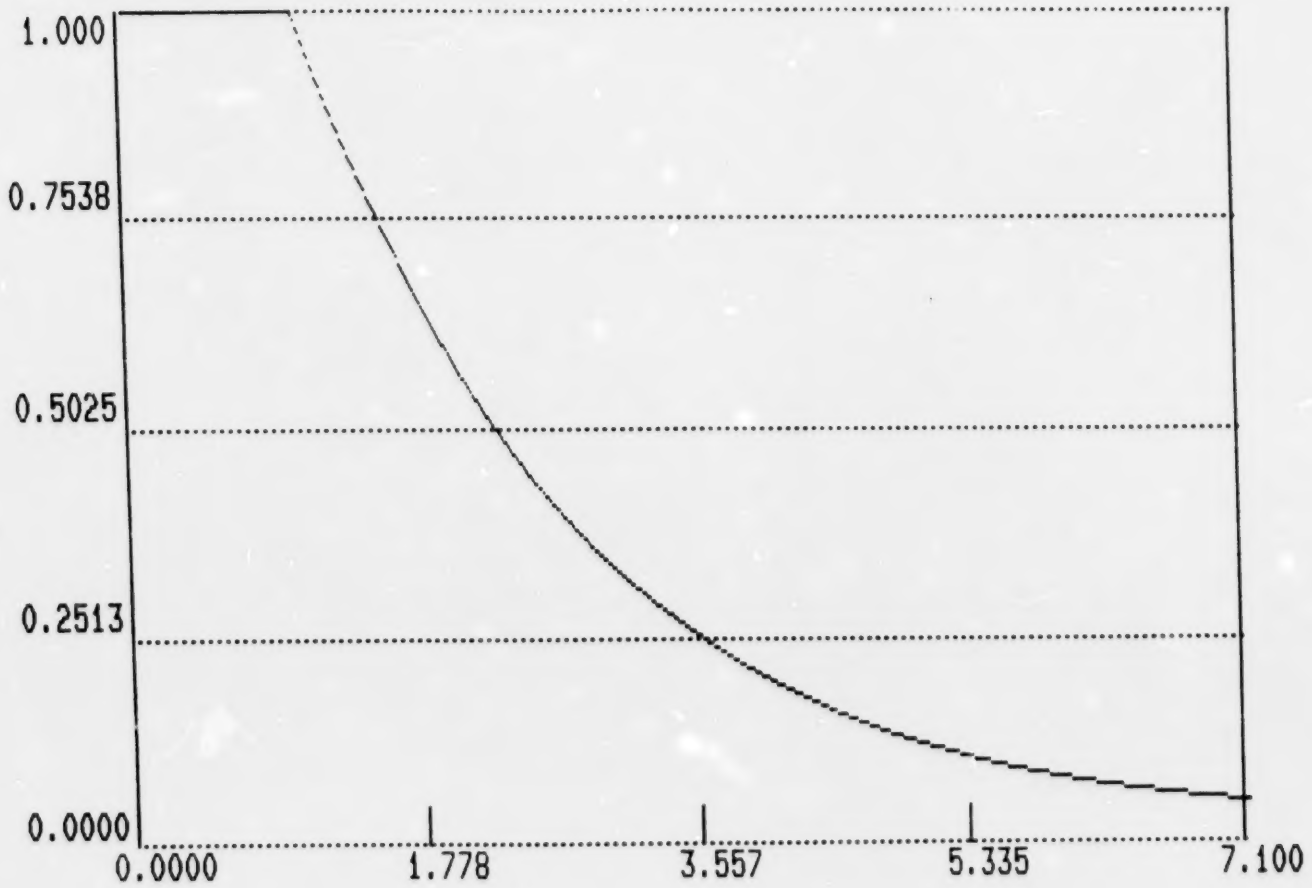


FIGURE 15. PROBABILITY OF NON-DETECTION VS. FLAW SIZE

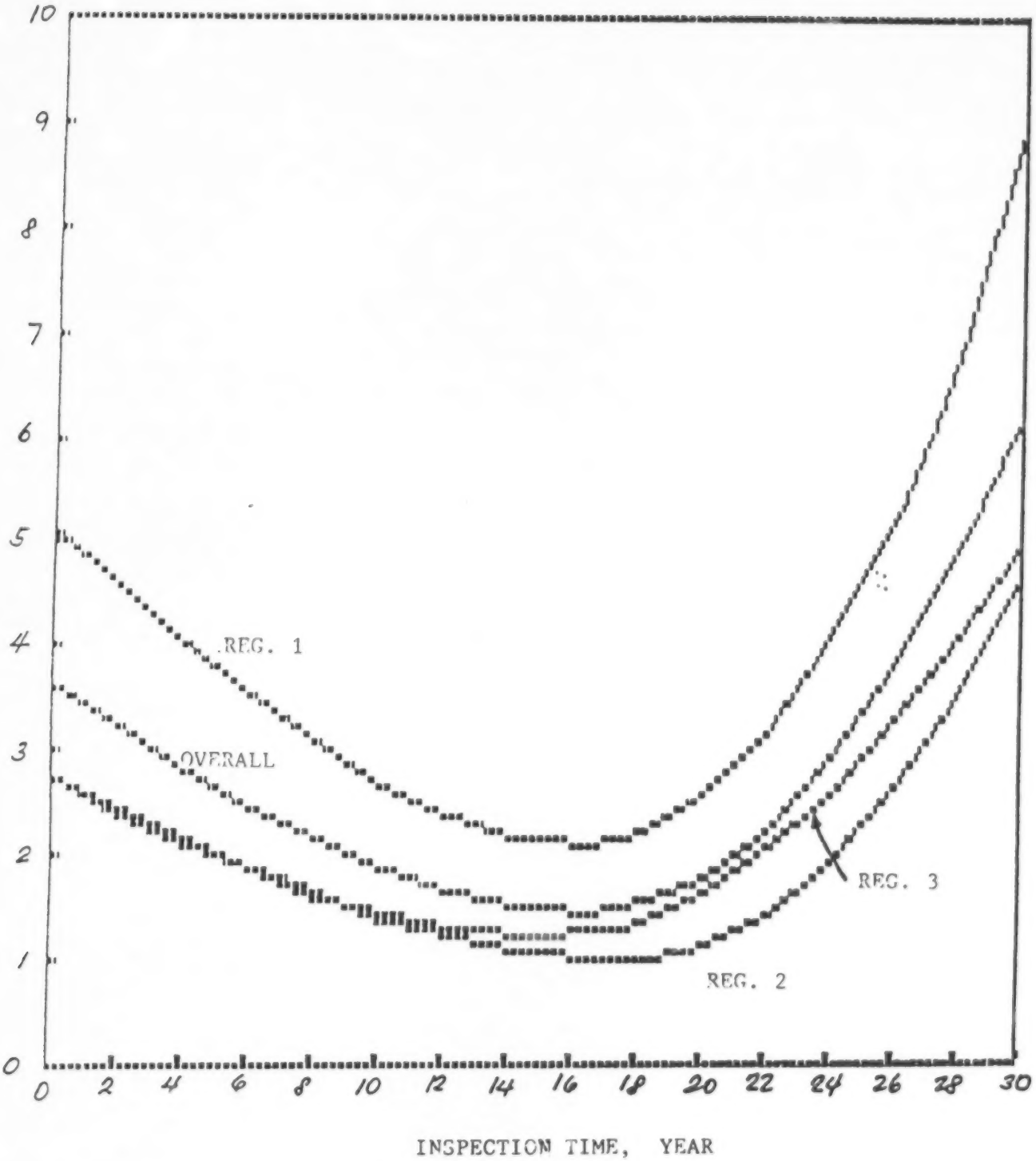


FIGURE 16. PREDICTED LEAK RATES, REPAIR SIZE AT 20% OF WALL THICKNESS (ONE INSPECTION AND REPAIR).

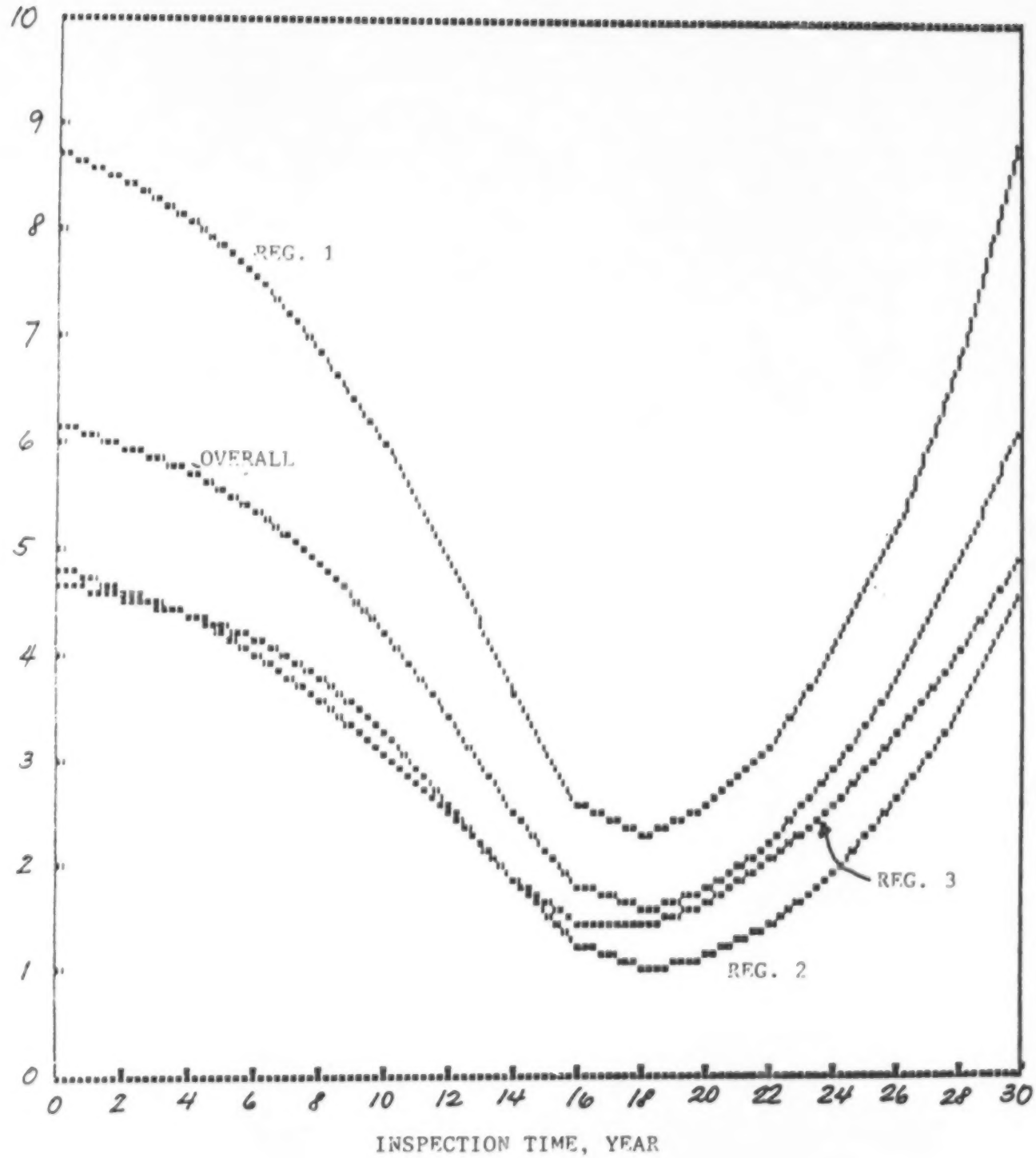


FIGURE 17. PREDICTED LEAK RATES, REPAIR SIZE AT 50% OF WALL THICKNESS (ONE INSPECTION AND REPAIR).

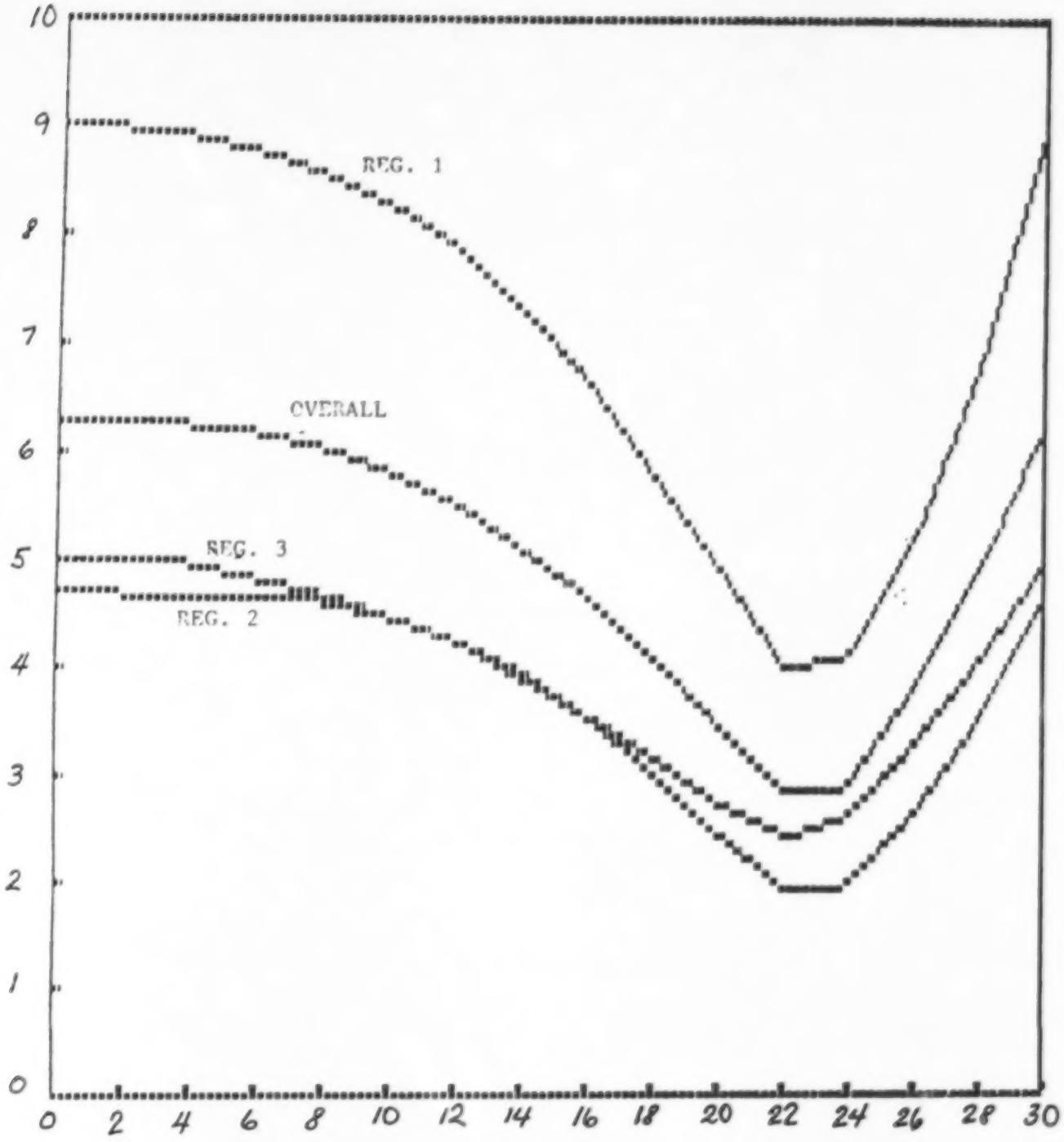


FIGURE 18. PREDICTED LEAK RATES, REPAIR SIZE AT 70% OF WALL THICKNESS (ONE INSPECTION AND REPAIR).

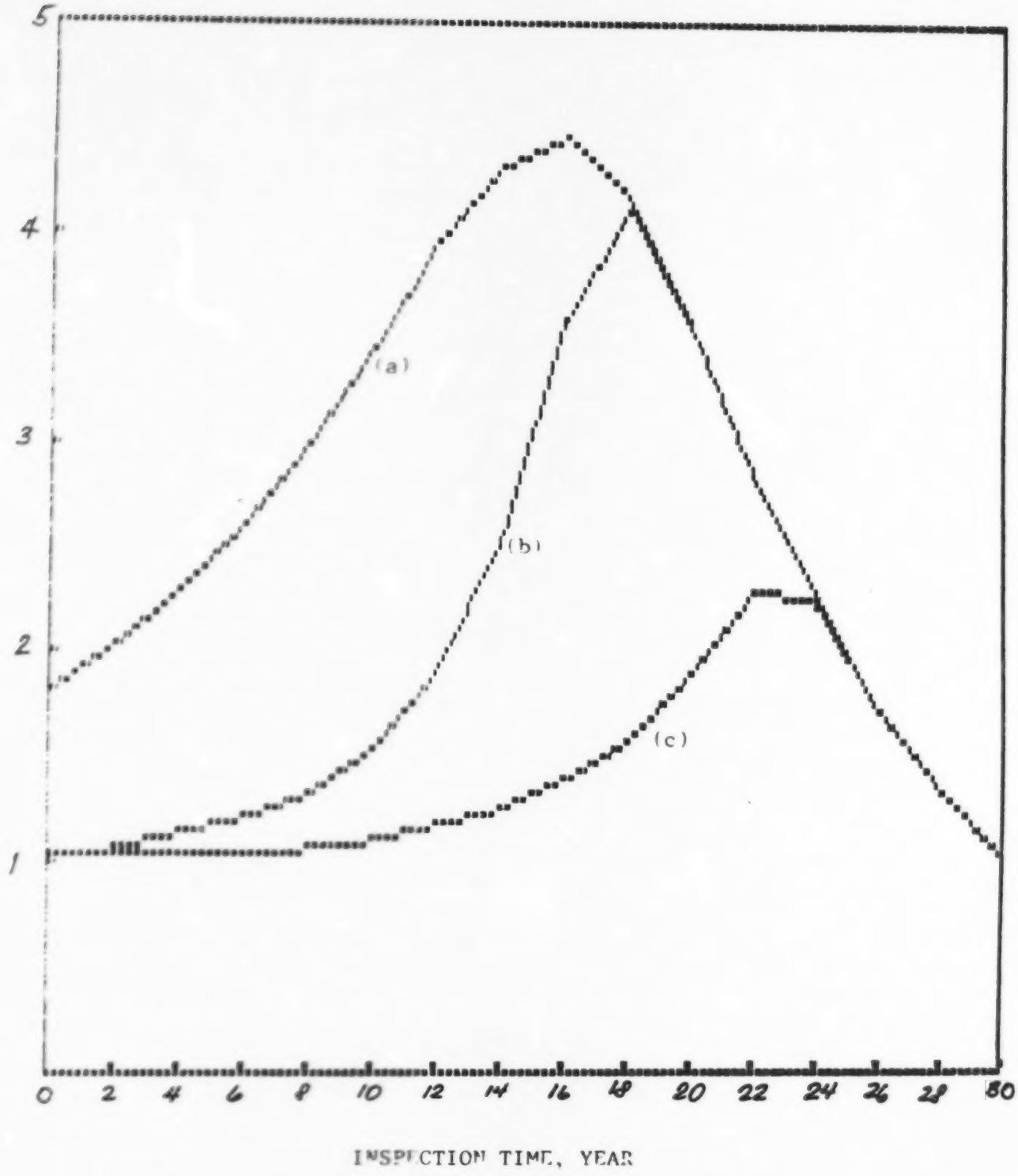


FIGURE 19. FACTOR OF IMPROVEMENT VS. INSPECTION TIME FOR THE OVERALL SYSTEM, REPAIR SIZE AT (A) 20%, (B) 50%, (C) 70% OF WALL THICKNESS. (ONE INSPECTION AND REPAIR).

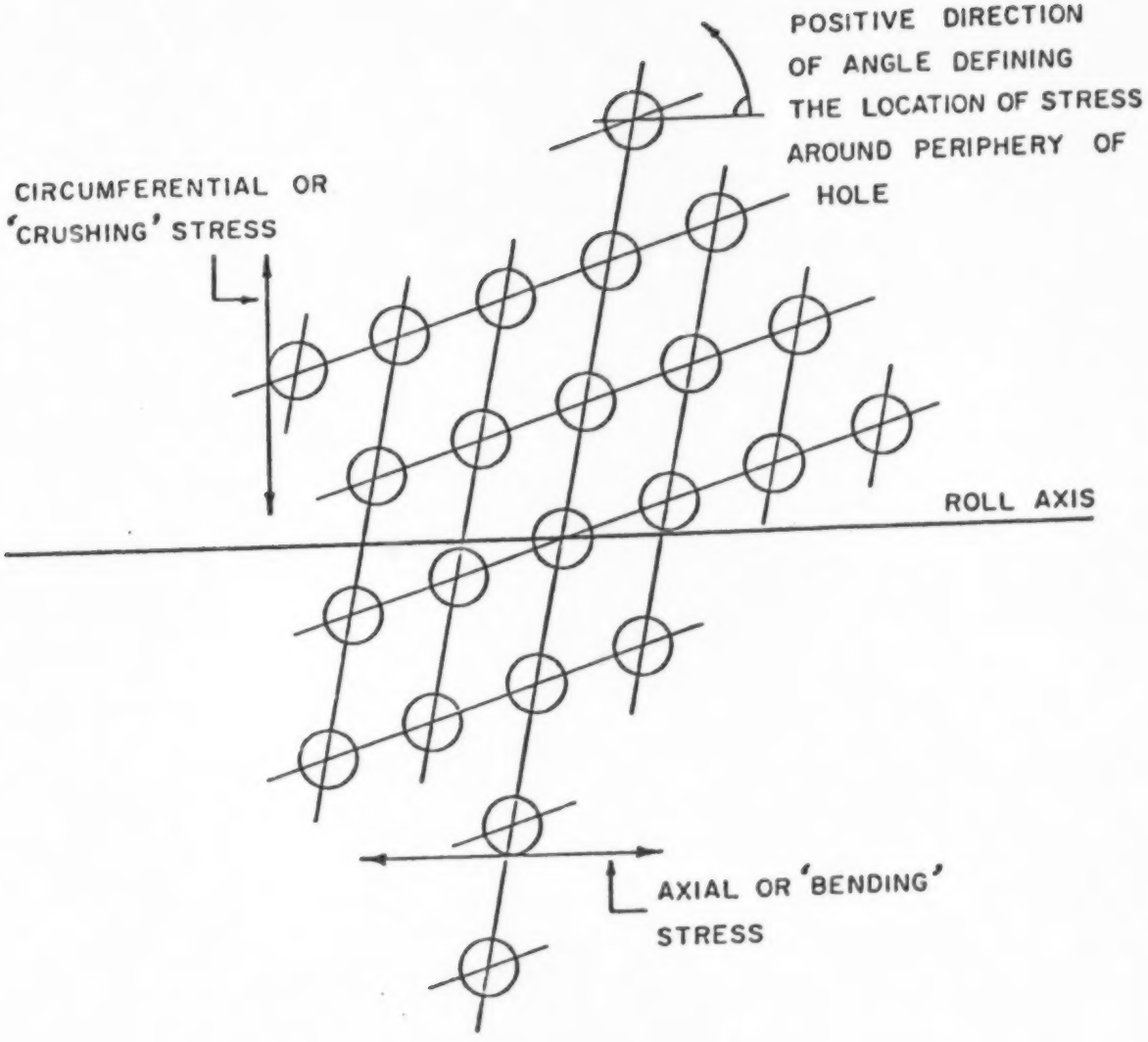


FIGURE 20. DRILLING PATTERN

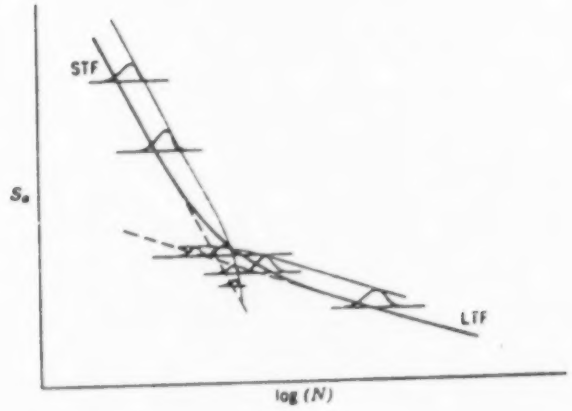


FIGURE 21. THE TWO-DISTRIBUTION PRESENTATION OF THE S-N CURVE.

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